When Neutrinos Encounter Nuclei

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

NuSTEC15 School – Okayama, November 2015

Jorge G. Morfín
Fermilab

The Exquisite Goal

and the Hazards that Block our Way

- Actually understanding the interaction of a lower energy neutrino in a massive nucleus is just as important as improving measurements of the oscillation parameters …
- except to the funding agencies!!

Main (4-Nail) Hazard: **Knowledge of ν-Nucleus Interactions**

What do we observe in our detectors constructed of heavy nuclei?

$Y_{\text{c-like}}\,(E_{\mathbf{m}})$: Yield in our detectors is dependent on

$\phi(E' \geq E_{\mathbf{m}})$ Neutrino Flux

$\otimes$

$\boldsymbol{\sigma_{c,d,e..}(E' \geq E_{m})}$ **Neutrino Cross Section**

$\otimes$

$\mathbf{Nuc_{c,d,e..\rightarrow c}\,(E' \geq E_{m})}$ **Neutrino Nuclear Effects**

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$\otimes$

$\mathrm{Nuc}_{c,d,e..\rightarrow c}(E' \geq E_{\mathbf{m}})$ **Neutrino Nuclear Effects**

Neutrino Nucleus Scattering

What do we observe in our detectors?

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

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

- $\mathbf{Y_{c\text{-}like}(E_m)}$ is the event energy and channel / topology of the event observed in the detector. It is called **c-like** at $\mathbf{E_m}$ since it is detected as channel c with energy $E_\mathbf{m}$ but may not have been so at interaction.

- The energy $E_\mathbf{m}$ is the sum of energies coming out of the nucleus that are measureable in the detector.

- That is the topology and energy measured in the detector is **not necessarily what was produced at the initial interaction. <u>The neutrino physics analyses depend on the initial interaction</u>.**

Neutrino Nucleus Scattering

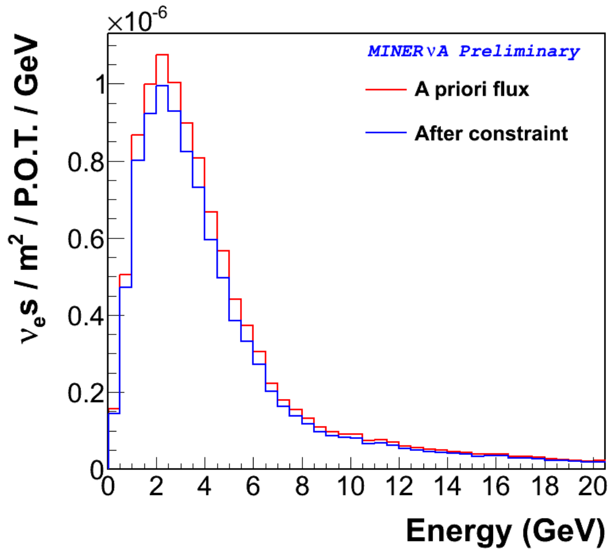
Neutrino Flux Term: $\phi_\nu(E' \geq E_m)$

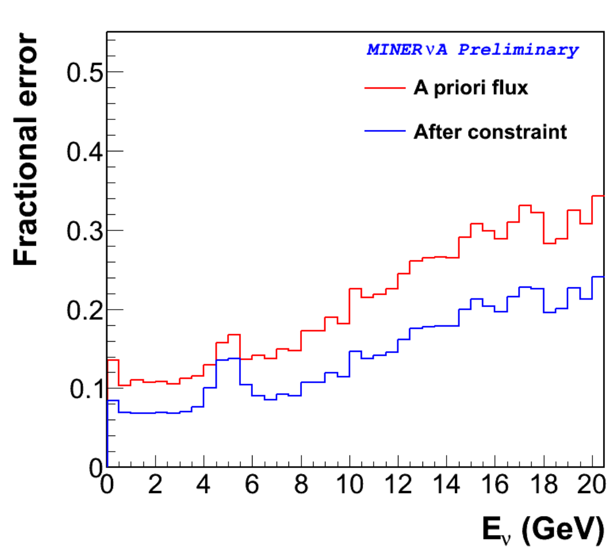
In-situ Flux Measurement: ν – e scattering

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F{}^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

G_F and θ_W: well-known electroweak parameters

- Using ν – e results, we can apply an additional constraint to the flux
- Here, the a priori is the HP corrected flux.





- Reduction of 5-10% in the flux prediction and > 15 % in predicted uncertainty as well.

Neutrino Nucleus Scattering

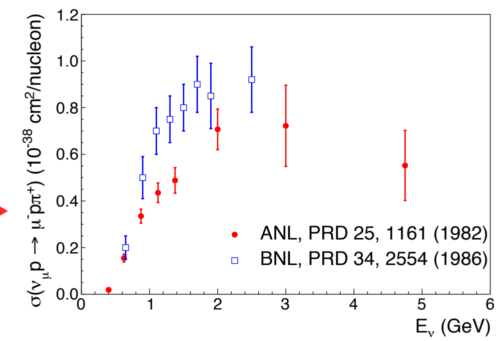
Cross Section Term: $\sigma_{c,d,e..}(E' \geq E_d)$

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

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

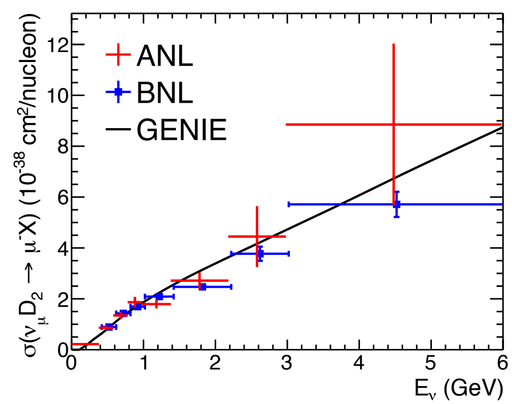
- $\sigma_{c,d,e..}(E')$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**

- **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.**

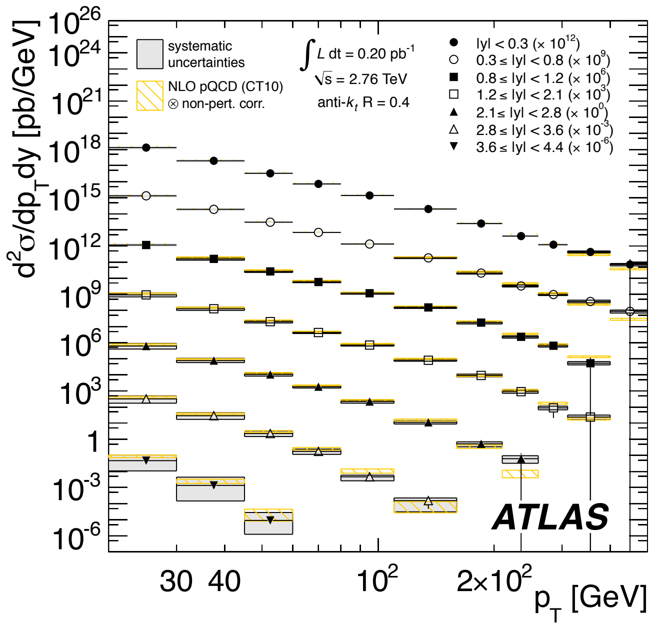
Wilkinson et al. – arXiv:1411.4482



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

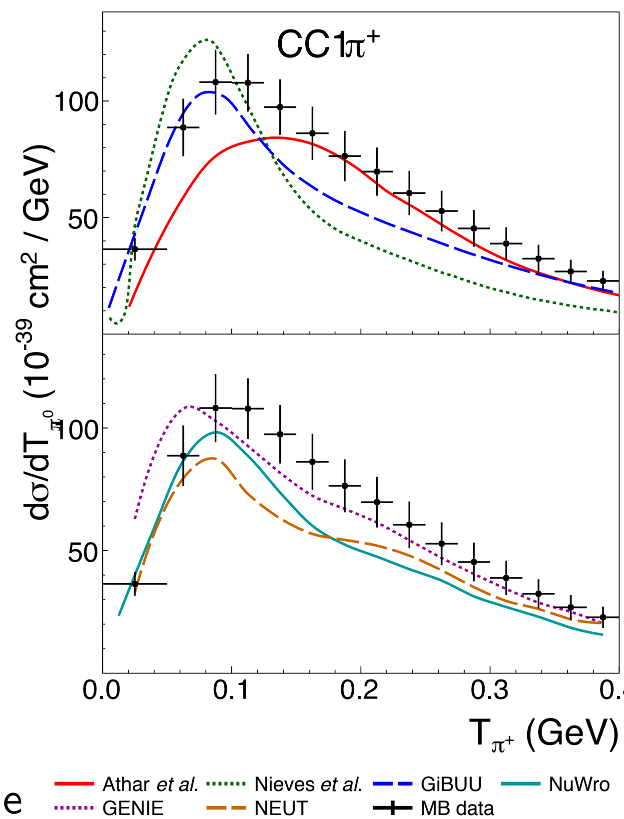
Do we Really Come Close to Understanding ν – A Cross sections

ATLAS inclusive jet cross section



EPJC 73, 2509 (2013)

$\nu_\mu\ CH_2 \rightarrow \mu^-\ \pi^+\ X$

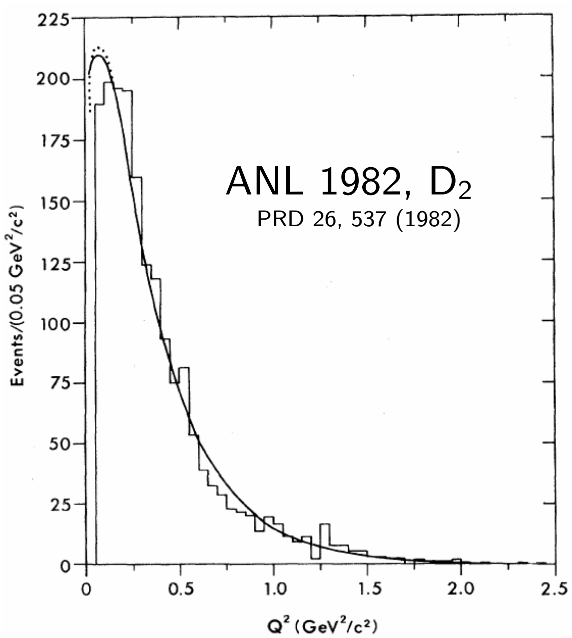


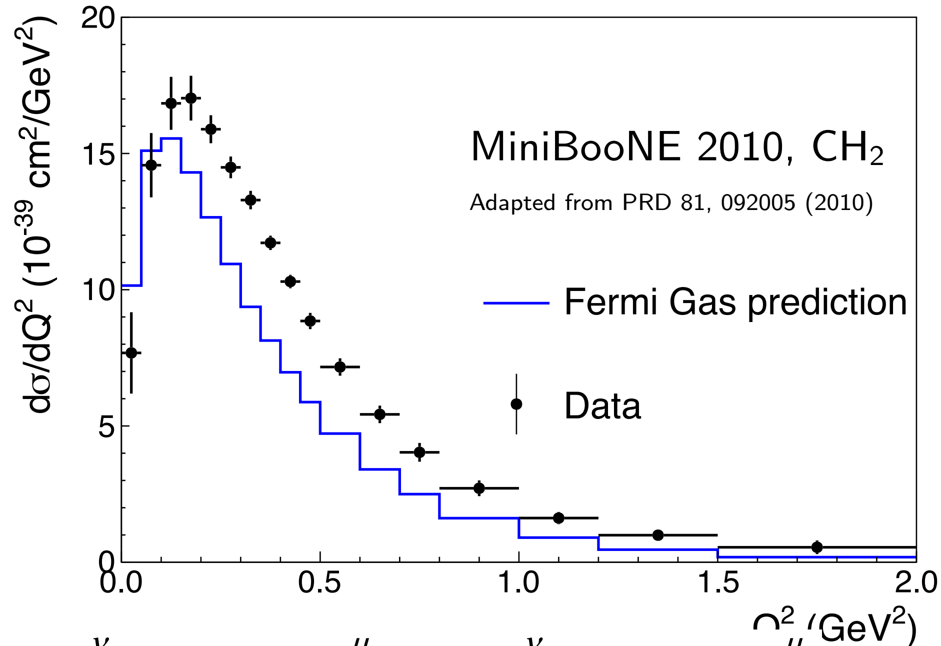
P. Rodrigues, arXiv:1402.4709 (NuInt 2012)
Data from PRD 83, 052007 (2011)

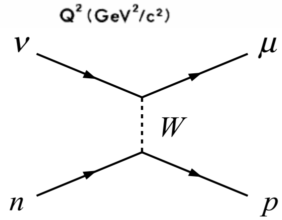
- Universal model, many orders of magnitude
- Wide variation in model predictions

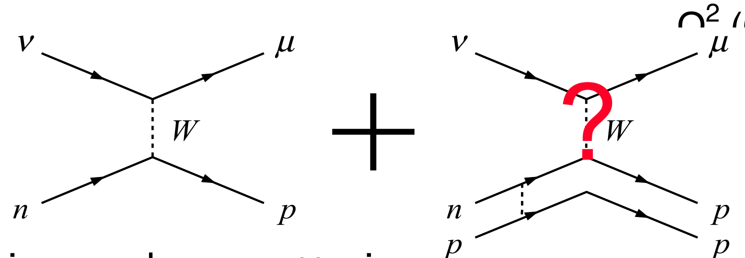
Charged-current Quasielastic (CCQE) ν scattering

- $\nu_\mu + n \rightarrow \mu^- + p$
- Two-body kinematics $\Rightarrow$ Important signal process for oscillation expts









- $d\sigma/dQ^2$ shape understood in neutrino-nucleon scattering
- Nuclear model: independent nucleons in Fermi gas missing something?

Neutrino Nucleus Scattering
Nuclear Effects Term: $\mathbf{Nuc}_{c,d,e..\rightarrow c}(E' \geq E_d)$

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

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

- **$\mathbf{Nuc}_{c,d,e..\rightarrow c}(E' \geq E)$ – Nuclear Effects**
  - **The Supreme Mixer / The Grand Deceiver** – a migration matrix that mixes produced channel and energy to detected channel and energy.
  - There are many nuclear effects that have to be considered that take the interaction of a neutrino with energy E' with the bound nucleon(s) and producing initial channel d,e… that will then appear in our detector as energy E and channel c.
  - The physics we want to study depends on the initial interaction – not what we observe coming out of the nucleus. **How do we move detected quantities backwards through the nucleus?**

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

1) Measure neutrino energy and event topology in the near detector.

2) Use the **nuclear model** to take the detected energy and topology back to the initial interaction energy and topology.

3) Project this initial interaction distribution, perturbed via an oscillation hypothesis that changes ϕ_ν, to the far detector.

4) Following the initial interaction, use the **nuclear model** to take the initial energy and topology to a detected energy and topology.

5) Compare with actual measurements in the far detector.

Critical dependence on the nuclear model even with a near detector!

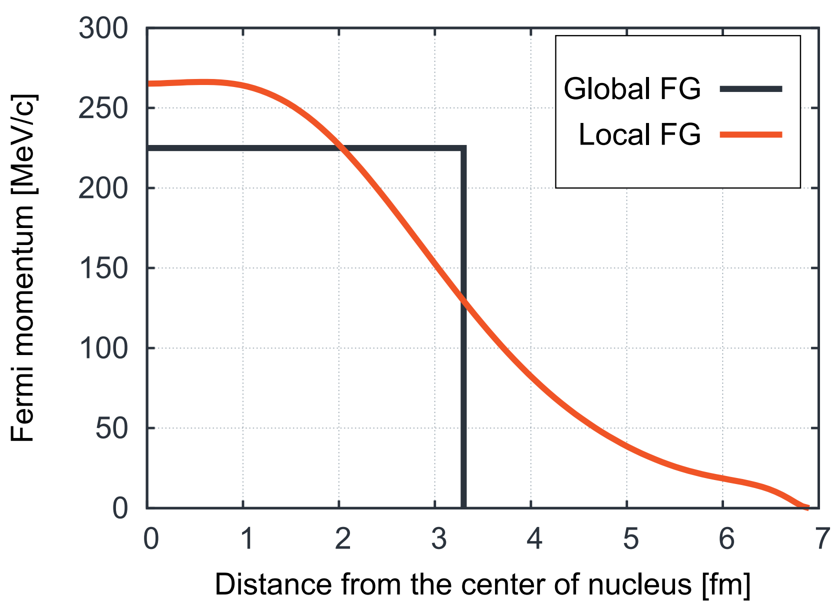
How do we constrain/improve the nuclear model?

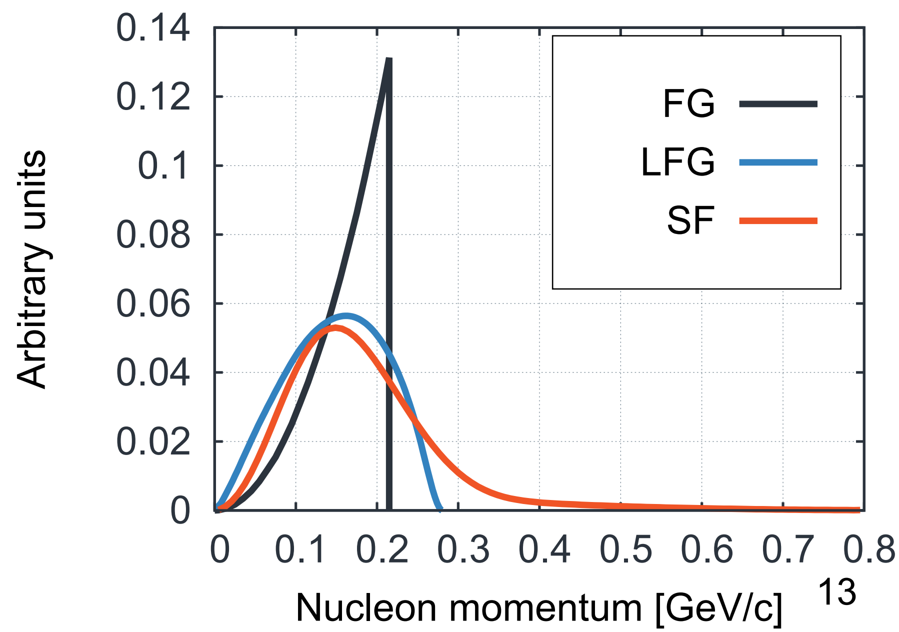
What are these Nuclear Effects **$Nuc_{c,d,e..\rightarrow c}$ (E' ≥ E)** in Neutrino Nucleus Interactions?

- Target nucleon in motion – classical Fermi gas model or spectral functions (Benhar et al.) or more sophisticated models.
- Certain reactions prohibited - Pauli suppression.
- Nucleon-nucleon correlations such as MEC and SRC and even RPA implying multi-nucleon initial states.
- Cross sections, form factors and structure functions are modified within the nuclear environment and parton distribution functions within a nucleus are different than in an isolated nucleon.
- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing detected energy.
  - Convolution of $\sigma(n\pi)$ x formation zone model x π-charge-exchange/ absorption.

Before the ν even interacts, what is the initial state of nucleons within the nucleus?

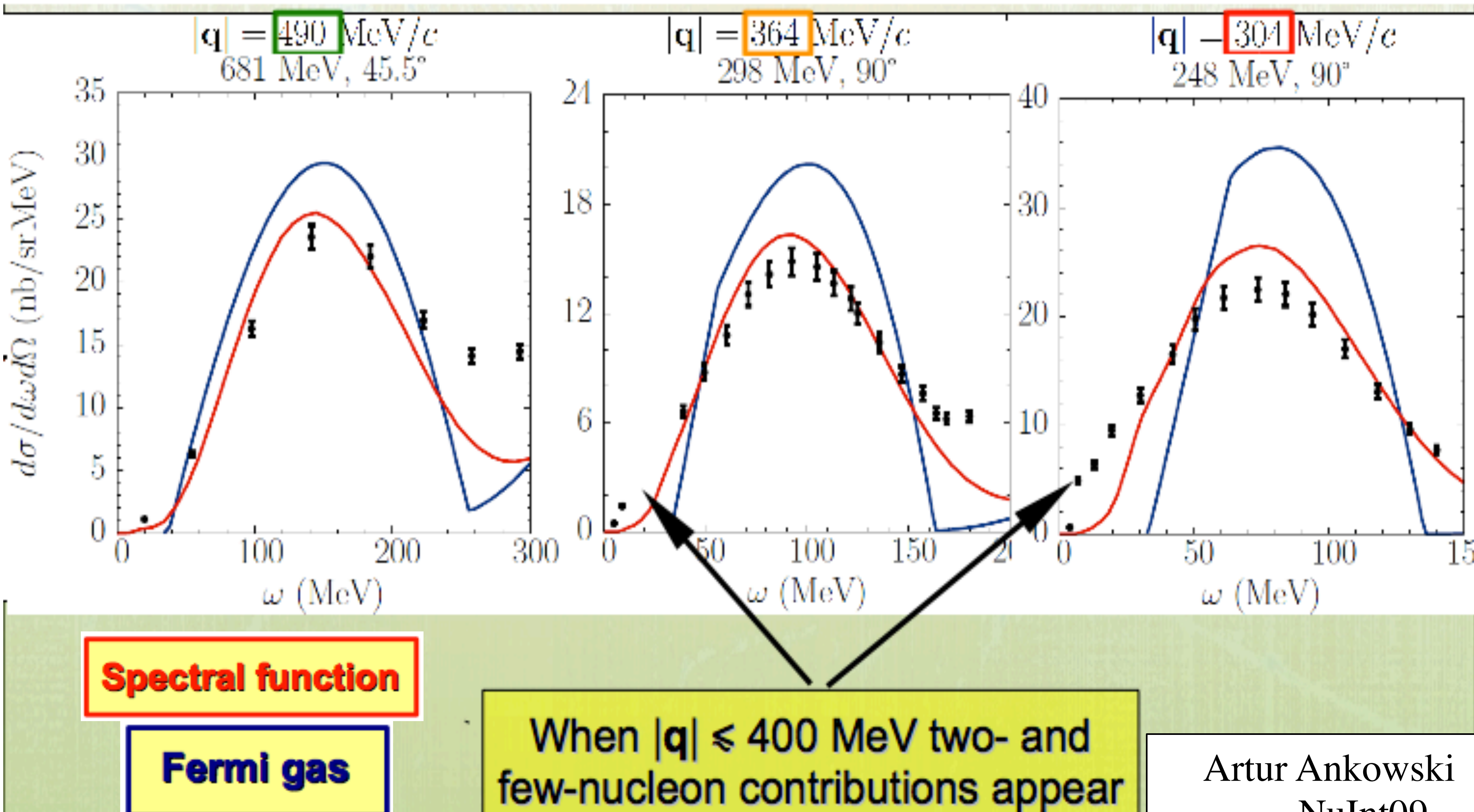
- **Fermi Gas**: Nucleons move freely within the nuclear volume in a constant binding potential.
- **Spectral Function**: The probability of removing a nucleon with momentum $\vec{p}$ and leaving residual nucleus with excitation energy *E*. Allows off mass shell nucleons.





Target Nucleon in Motion – Fermi Gas (still in many models) vs Spectral Function. A step up in sophistication

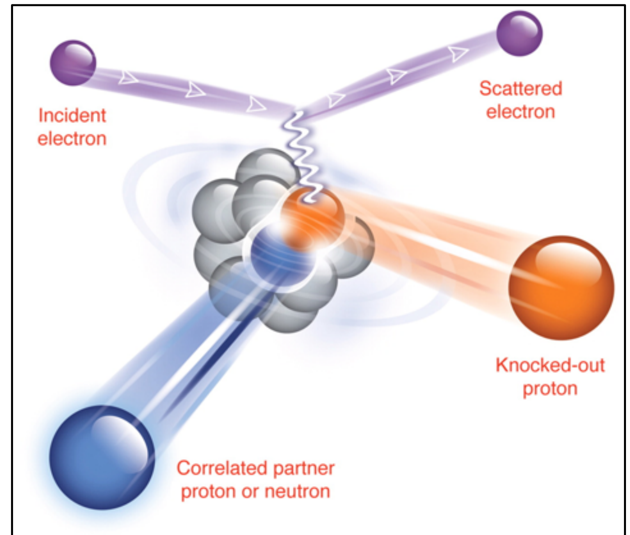
Superior particularly as Q Decreases



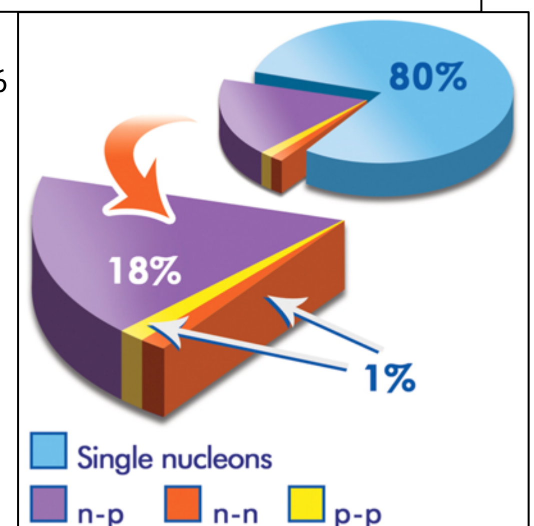
Artur Ankowski
NuInt09

Independent Nucleons?
Nucleon-Nucleon Correlations

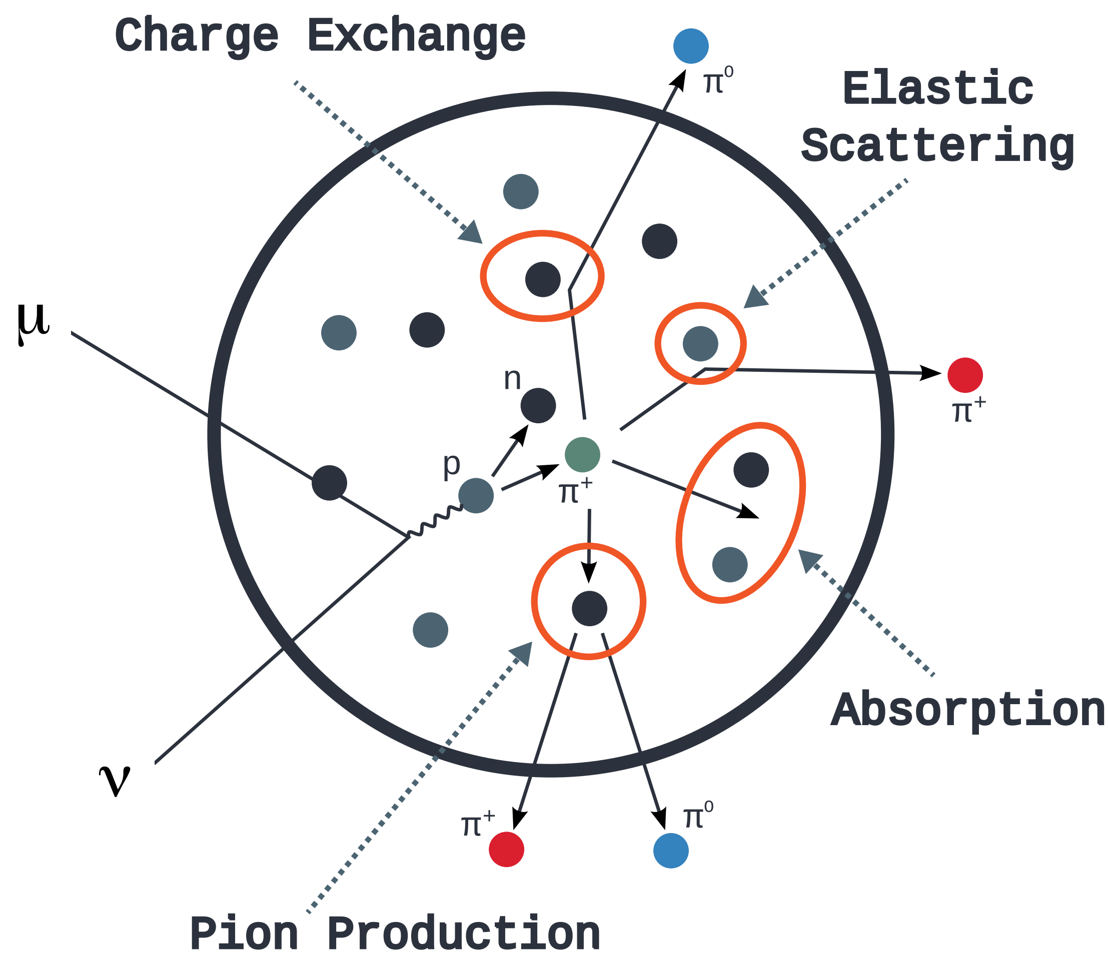
- Electron scattering
  - Measurements on ^{12}C indicate 20% correlated nucleons with mostly **np** pairs in the initial state.
- Neutrino scattering
  - Implies initial produced state in neutrino scattering of **nn in antineutrino** and **pp in neutrino** CC scattering.
  - For other forms of correlation, final state depends on model.
  - **Of course, what we eventually detect can be modified by Final State Interactions when interpreting neutrino scattering data.**



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



Final State Interactions (FSI)



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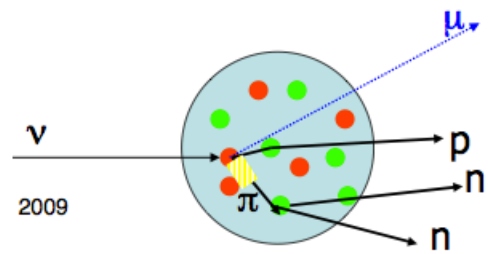


- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy. Currently using mainly **cascade models for FSI**.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons.
- Final state 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%

Neutrino Nucleus Scattering

Putting it all together: The Nuclear Model

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

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

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

- The community models these last two terms in **event generators**:
  - 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 neutrino experiments.
- Current Generators used by experimental community – each with their own models 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 used to check other generators

How Good are these Nuclear Models?

Addressing this question at this school?

How Good are these Nuclear Models?

Addressing this question in this talk?

We did get an answer!

What is inside MC generators...

...and why it is wrong

Tomasz Golan

University of Rochester / Fermilab

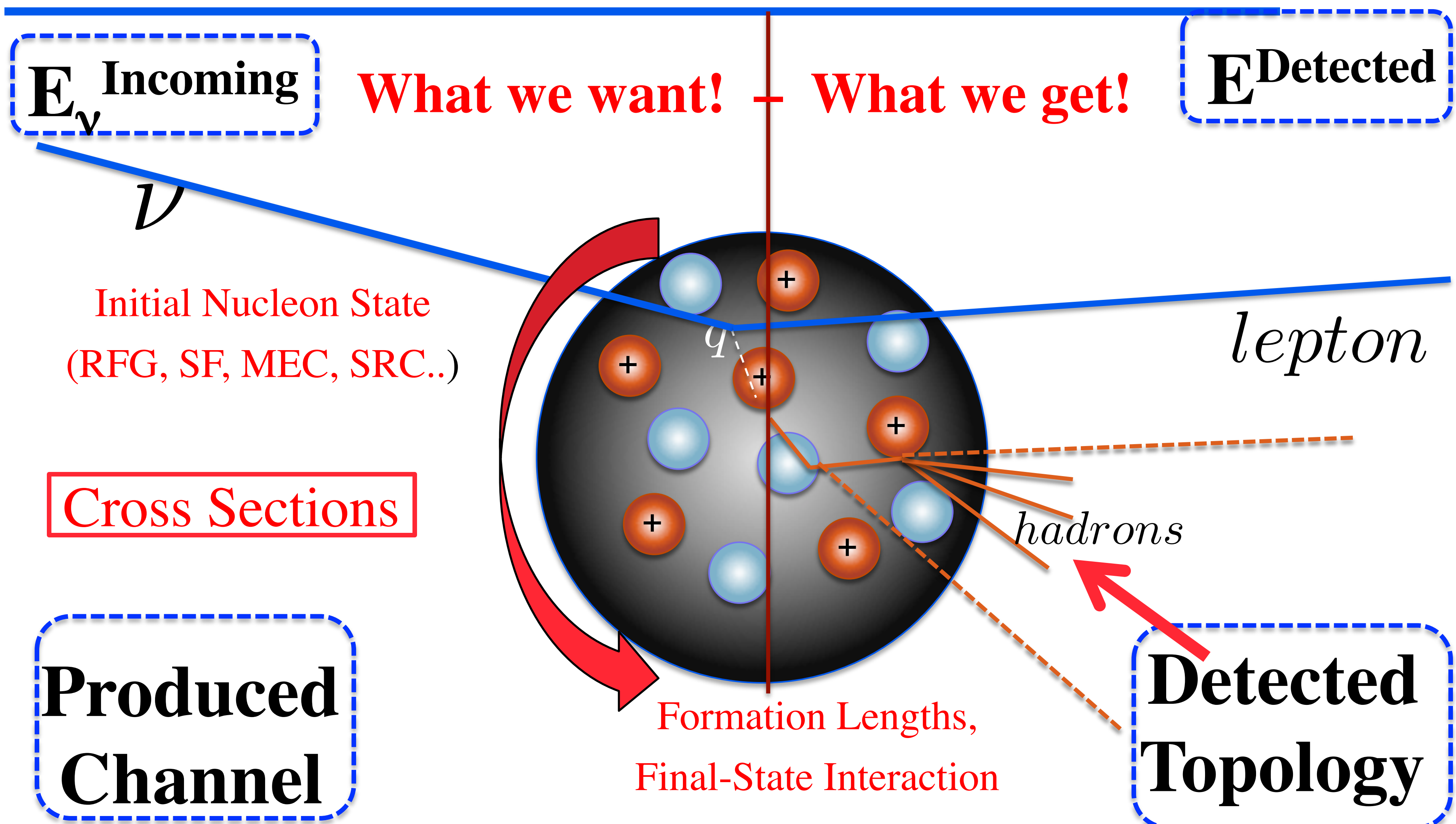
NuSTEC, Okayama 2015

Where we are depends on which nuclear model / generator we use!

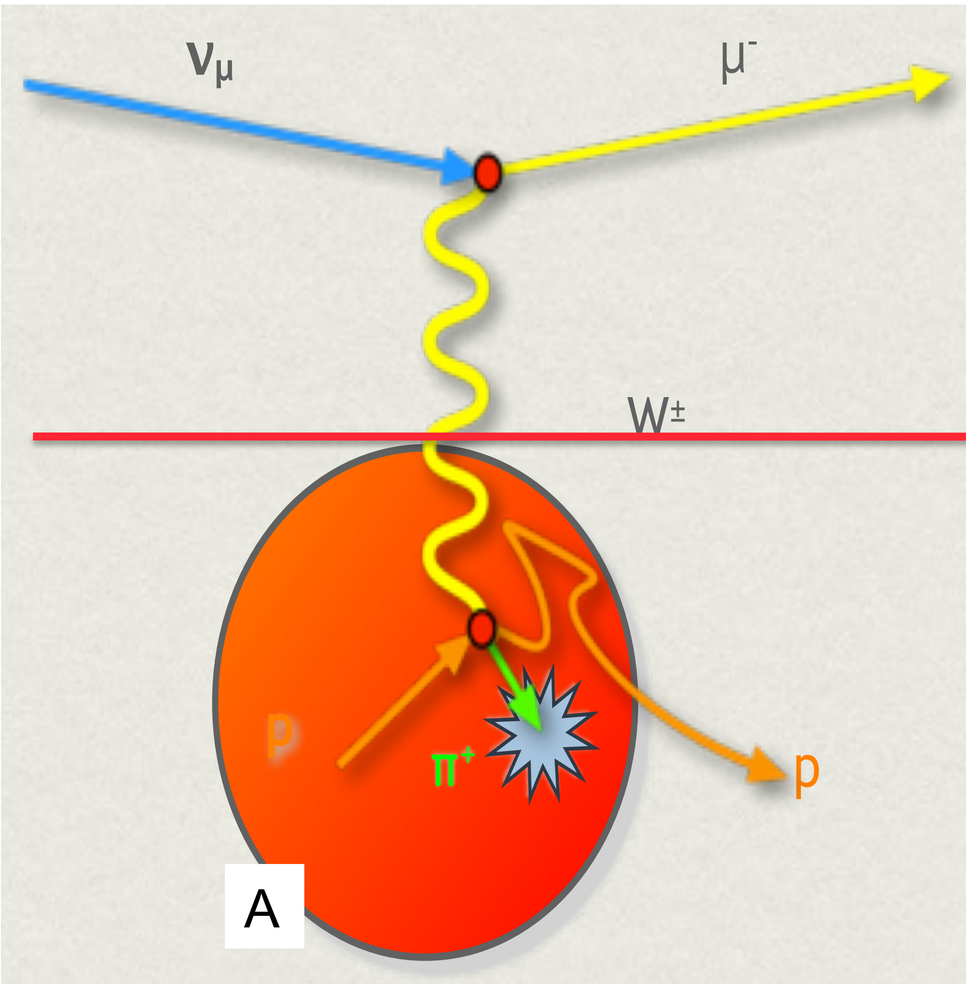
Where are we?

Map at Great Wall

Nuclear Physics of GeV ν-nucleus Interactions



Understanding Effects of the Nucleus
Leptonic vs Hadronic Clues



- **Lepton:**
- Provide information on initial interaction on nucleon within the nucleus.
- **Initial Nucleon State**
  - **Relativistic Fermi Gas Model**
  - **Local Fermi Gas Model**
  - **Spectral Functions**
  - **Correlated Nucleons (RPA, MEC, SRC..)**

- **Hadrons:**
- Provide information on Final State Interactions within the nucleus.
  - **Note that correlated nucleons (RPA, MEC, SRC..) also undergo final state interactions.**

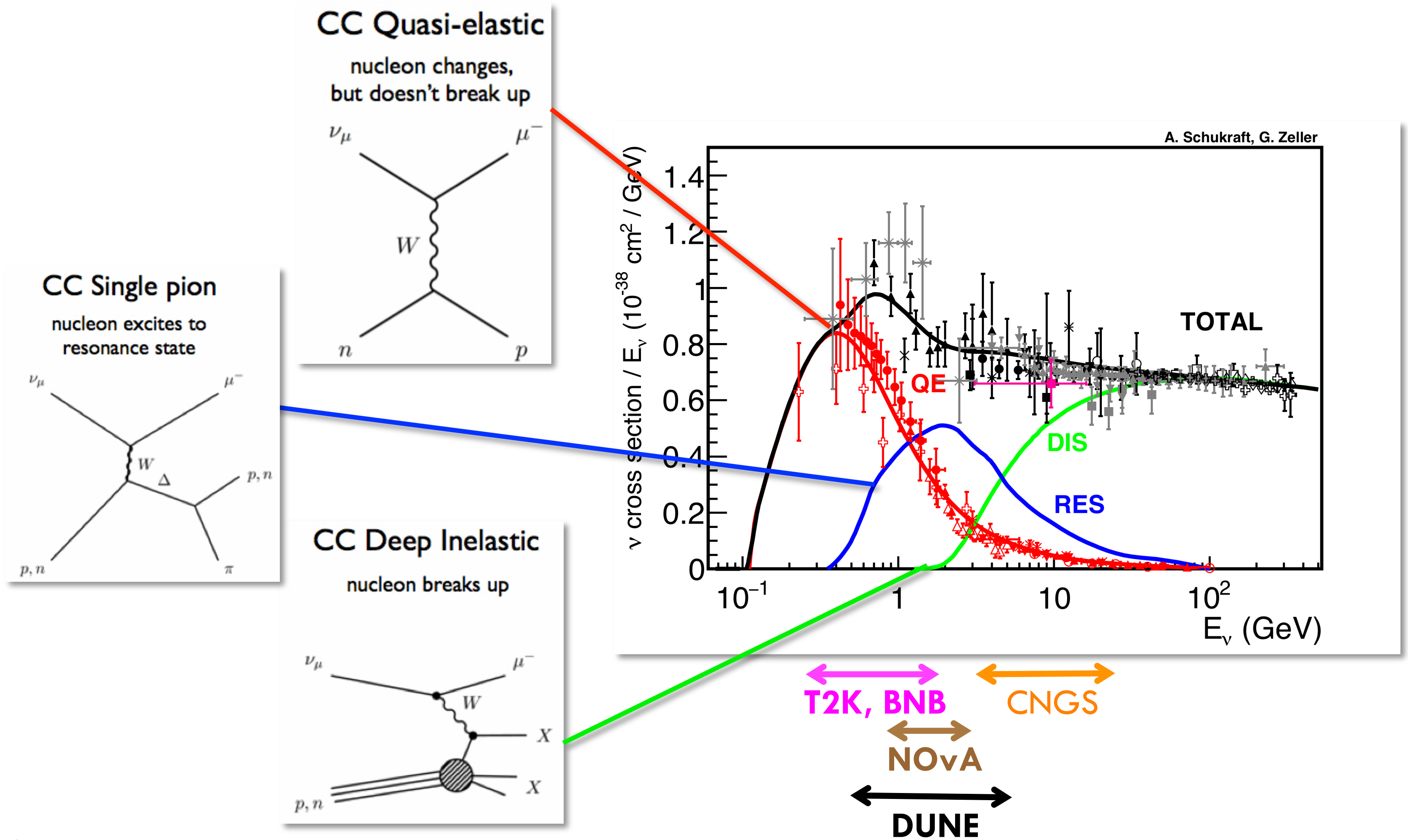
Important Contributors to Results in this Presentation

- Results from MINERvA that are mainly due to the analyses of:
  - Arturo Fiorentini – Rio de Janeiro (now York postDoc)
  - Aaron Higuera – Guanajuato (now Huston postDoc)
  - Brandon Eberly- Pittsburgh (now SLAC postDoc)
  - Brian Tice - Rutgers (to ANL postDoc now Bloomberg capitalist)
  - Tammy Walton - Hampton (now Fermilab postDoc)
  - Trung Le - Rutgers postDoc
  - Carrie McGivern - Pittsburgh postDoc
  - Joel Mousseau - Florida (now Michigan postDoc)
- Borrowed freely from presentations of Steve Dytman and Sam Zeller

Dominant Interaction Modes

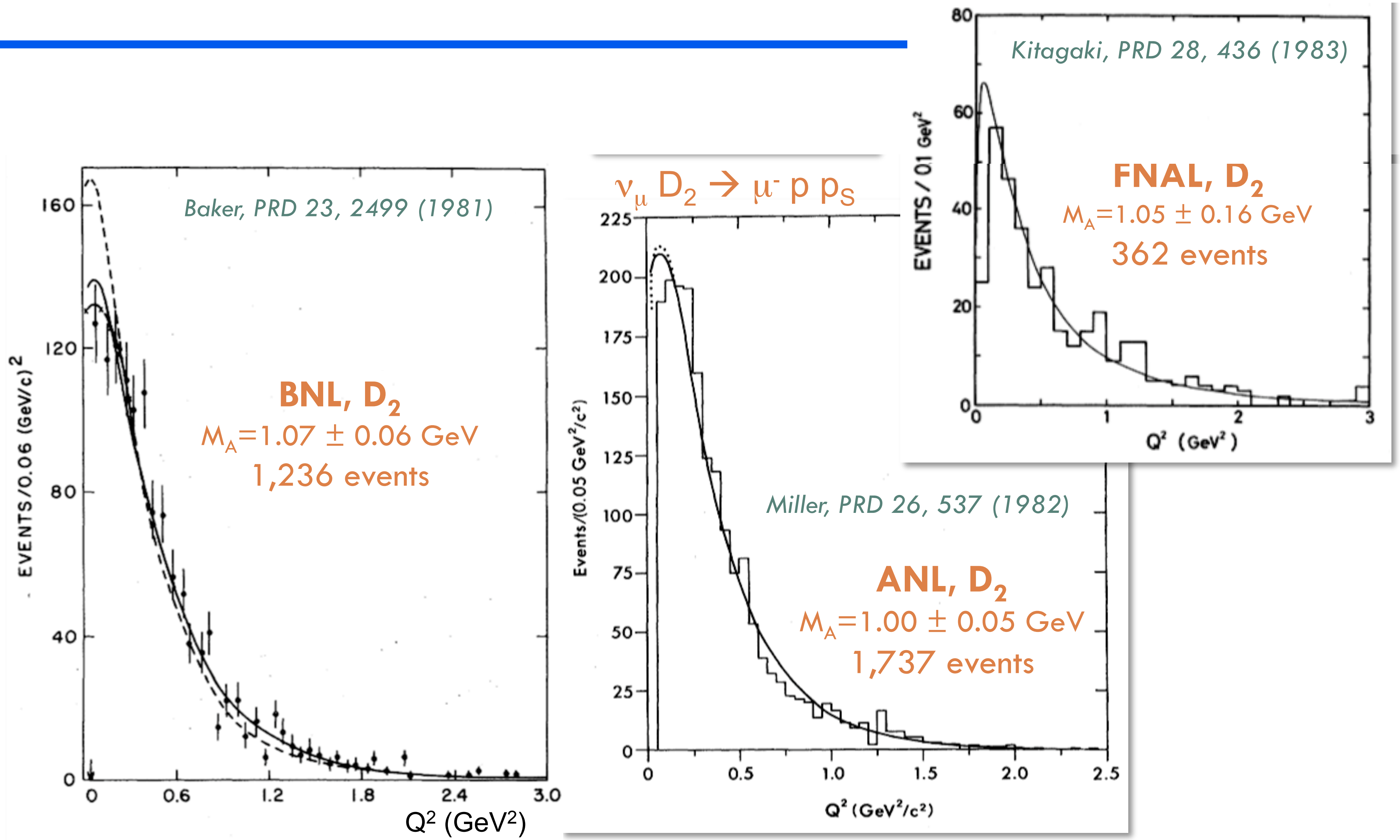
We essentially know the vector part of these interactions via CVC and e-A scattering.

The challenge is the axial-vector contribution!



First QE **Nucleon** Results Published in early '80s

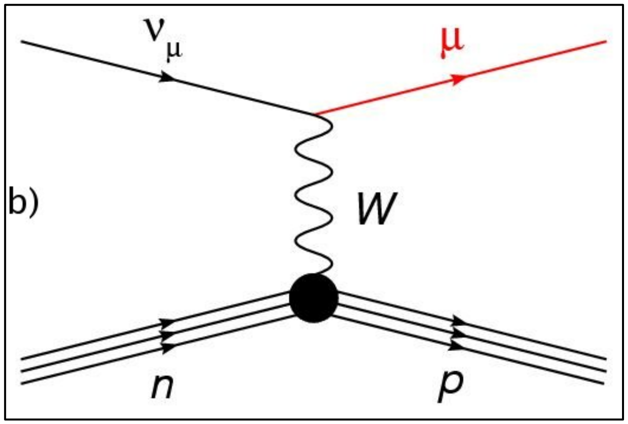
Good Agreement on the value of M_A



Where the real effects of nucleus-induced problems begin!
Quasi-elastic (QE) Neutrino **Nucleus** Scattering

Important for oscillation experiments

- A technique used by oscillation experiments, (particularly when blind to the hadronic final state), for analyzing quasi-elastic scattering, is to assume the ***nucleon is at rest!***
- One can then determine E_ν and Q^2 from lepton side kinematics only ("2-body interaction")



neutrino energy

$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\ell - \left[(M_n - E_B)^2 + m_\ell^2 - M_p^2\right]}{2\,[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

$$Q^2_{QE} = -m_\ell^2 + 2E_\nu^{QE}\left(E_\ell - \sqrt{E_\ell^2 - m_\ell^2}\cos(\theta_\ell)\right)$$

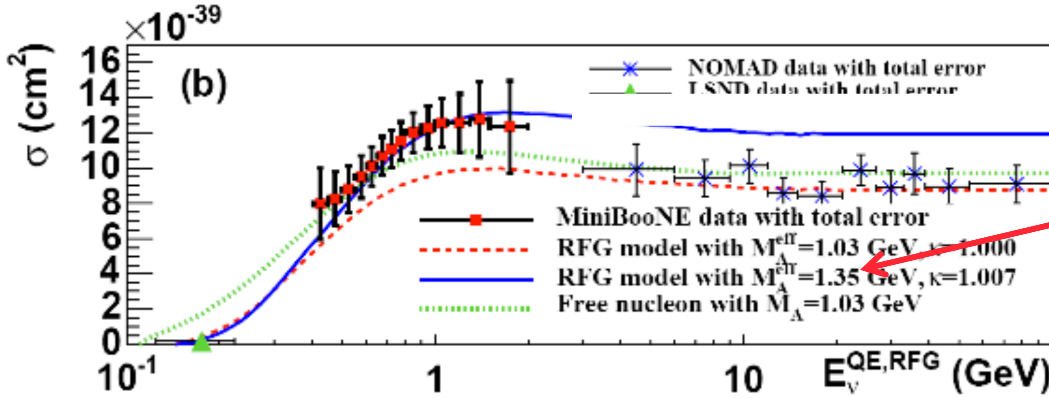
4-momentum transferred

M_n = neutron mass
M_p = proton mass
E_B = separation energy
m_ℓ = lepton mass
E_ℓ, θ_ℓ = lepton energy and angle

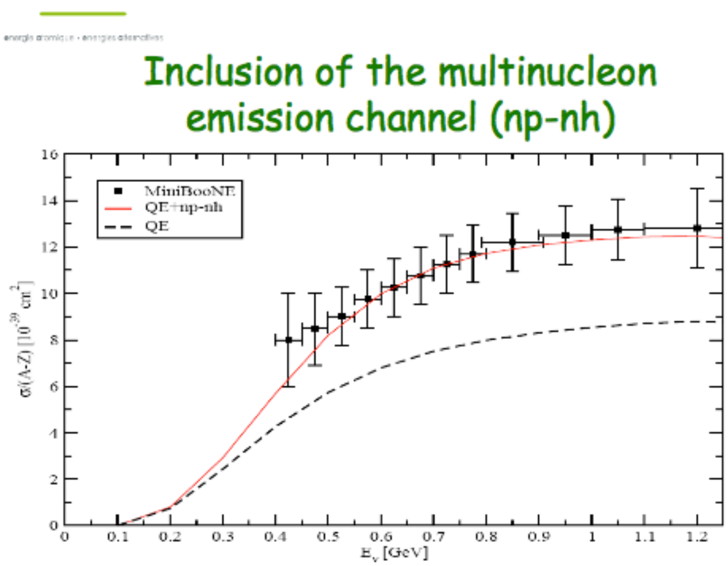
The MiniBooNE QE Analysis:

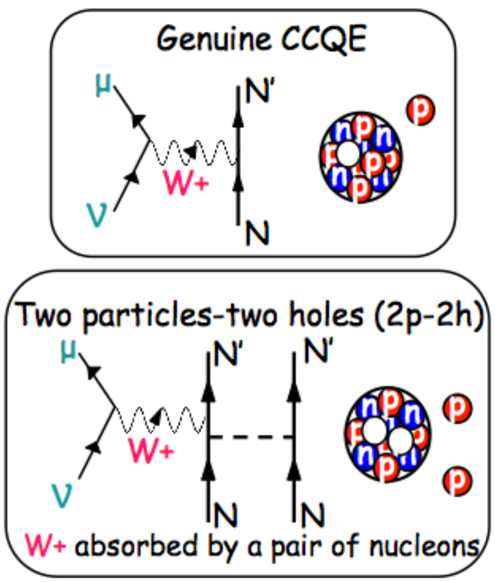
Introduction of nucleon-nucleon correlations

Meson Exchange Currents – 2p2h Effects



M_A = 1.35 GeV



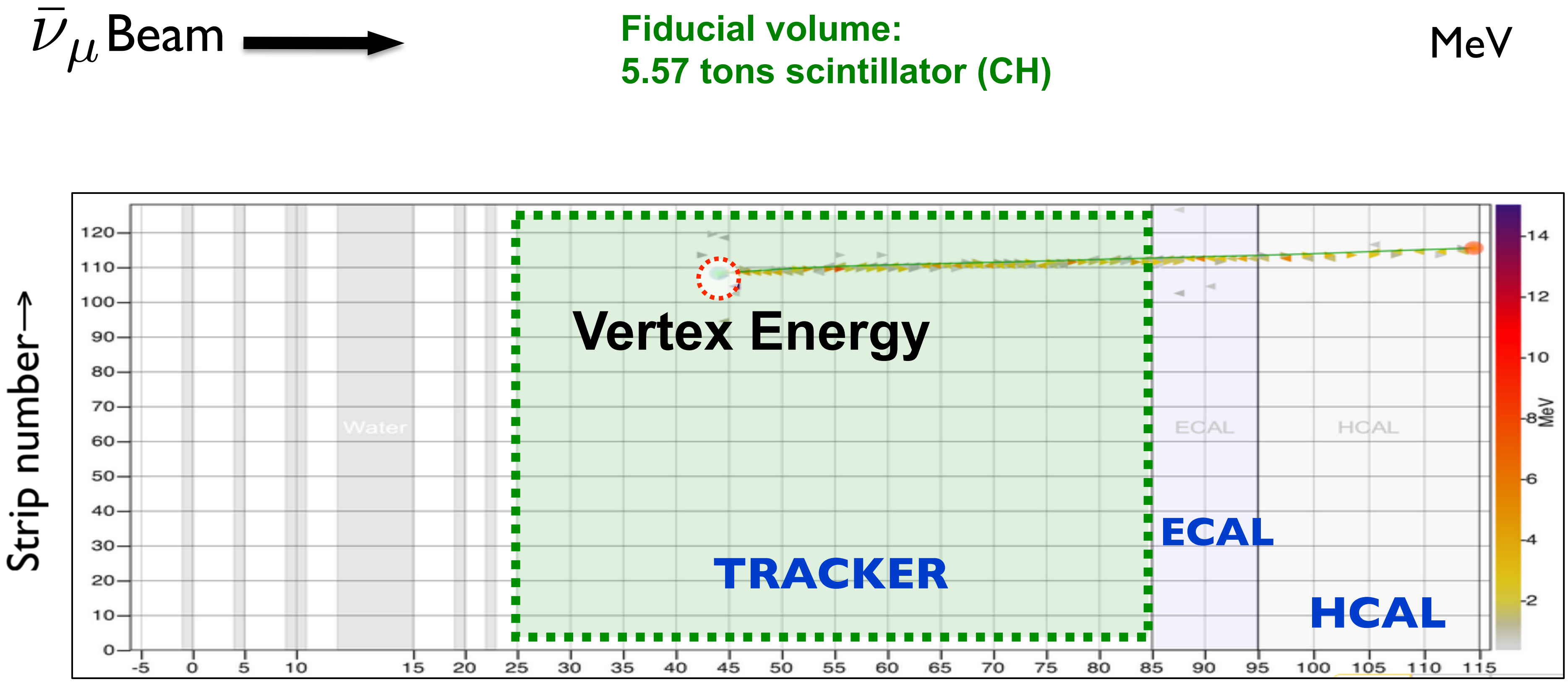


M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

MINERvA: Single Muon (lepton side) QE-like Analysis

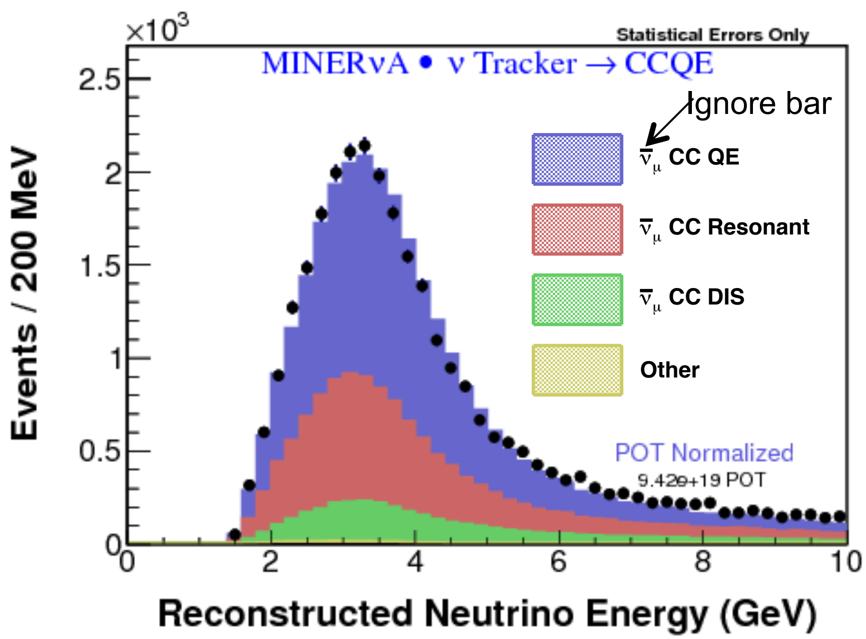
Also sees evidence for nucleon-nucleon correlation effects

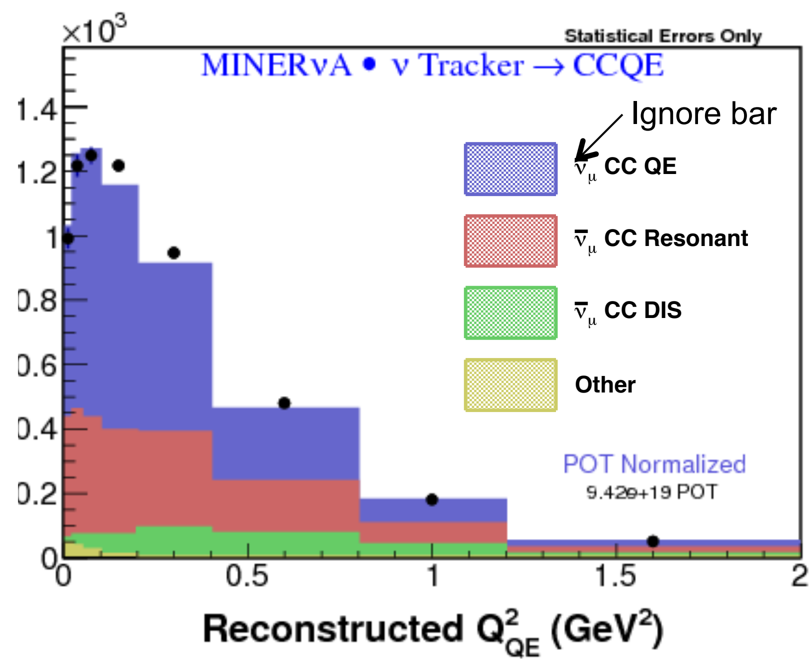
$\bar{\nu}_\mu$ Beam



MINERνA: Single Muon QE-like Analysis

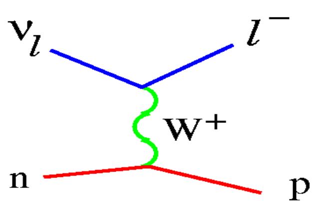
- According to this nuclear model (GENIE) analysis, the resulting QE-like sample is 49% QE with large QE-like contributions from resonant, transition and even DIS events appearing, through nuclear effects, as QE in the detector.





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

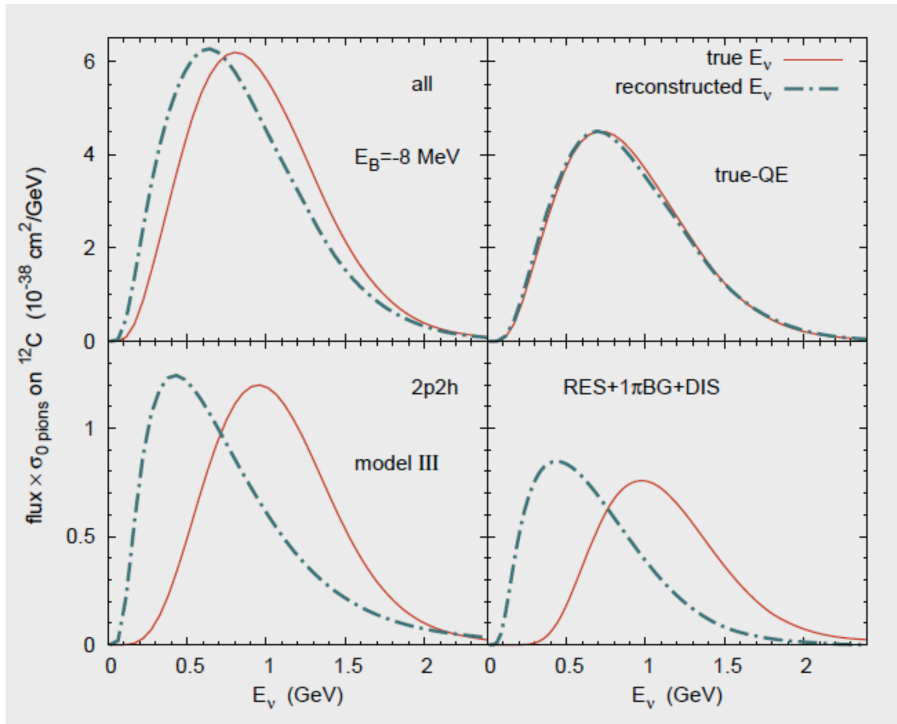
- Using the outgoing lepton to determine E_{QE} and Q_{QE}:



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

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!



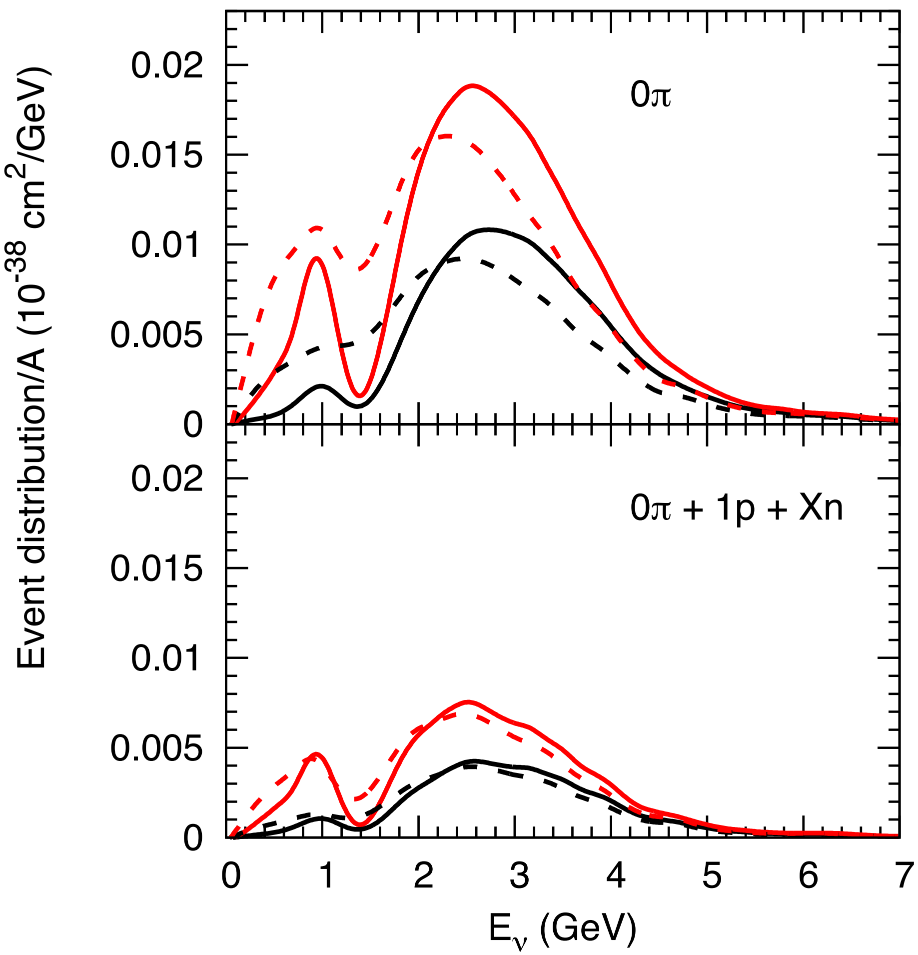
U. Mosel GiBUU

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

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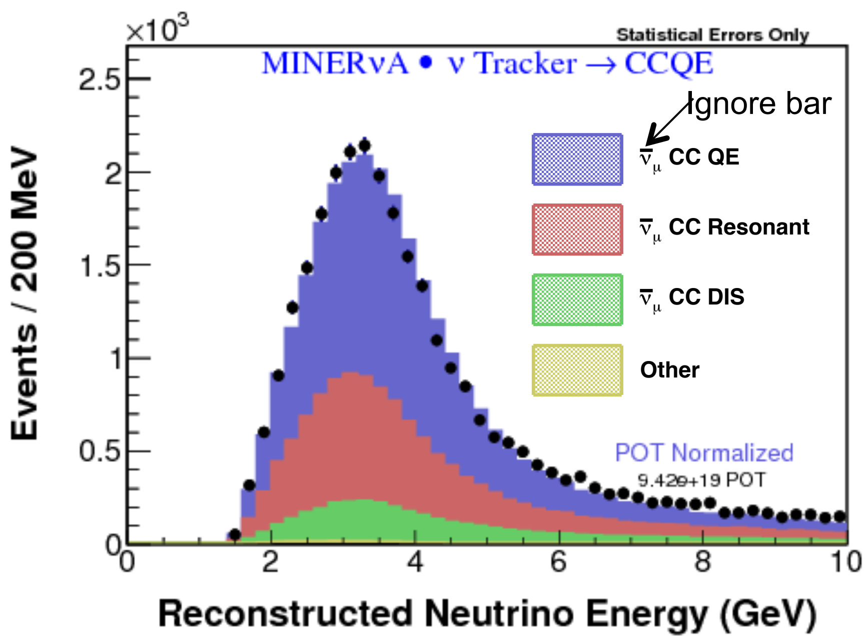
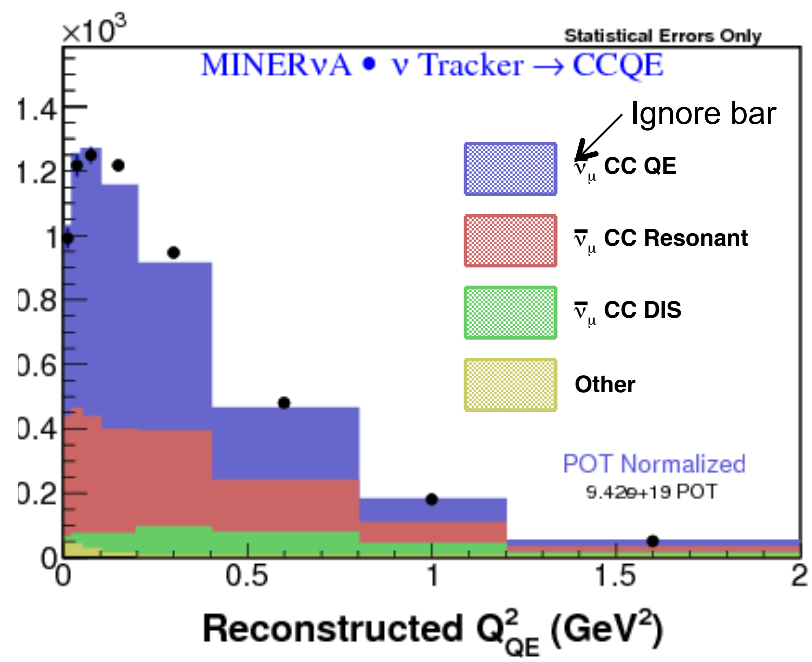
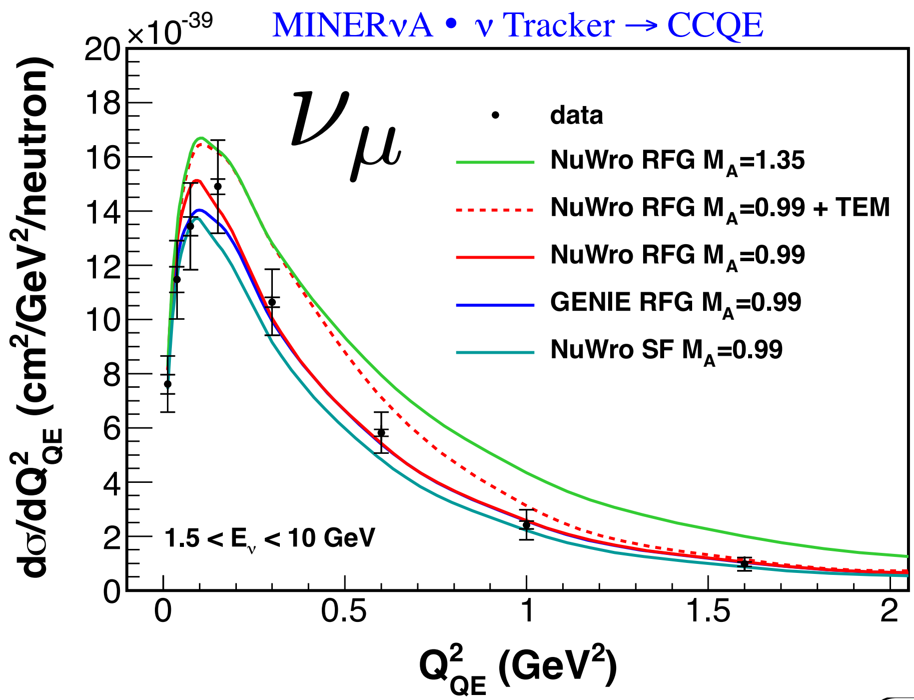
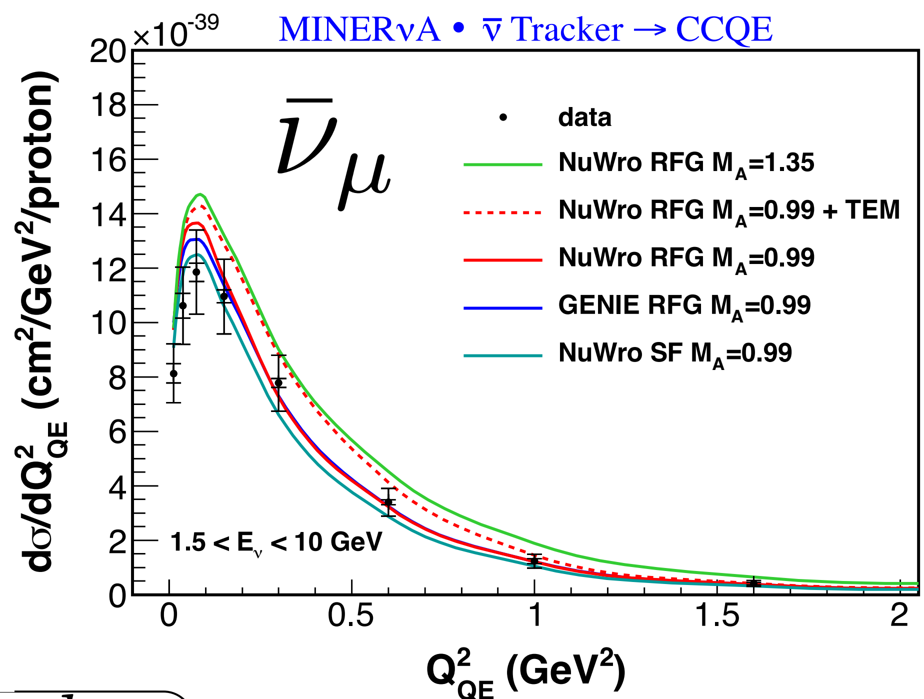




MINERvA: Single Muon QE-like Analysis



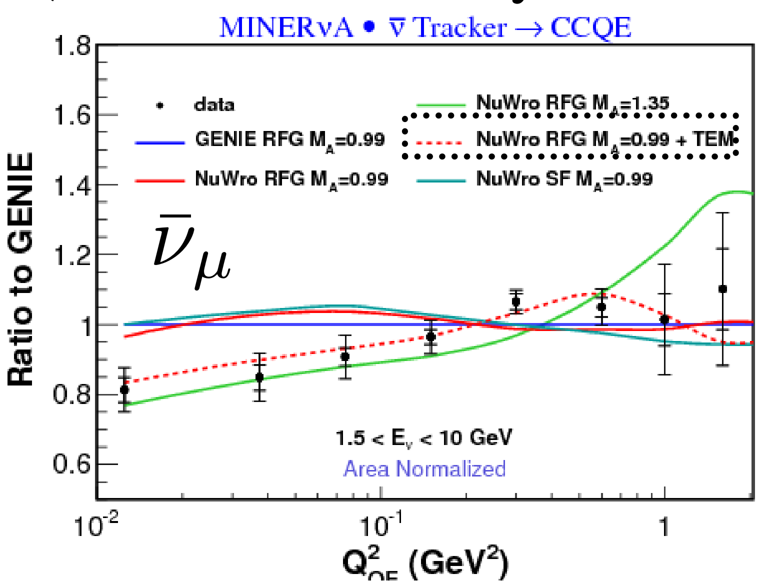


$$\boxed{\frac{d\sigma}{dQ^2_{QE}}}$$

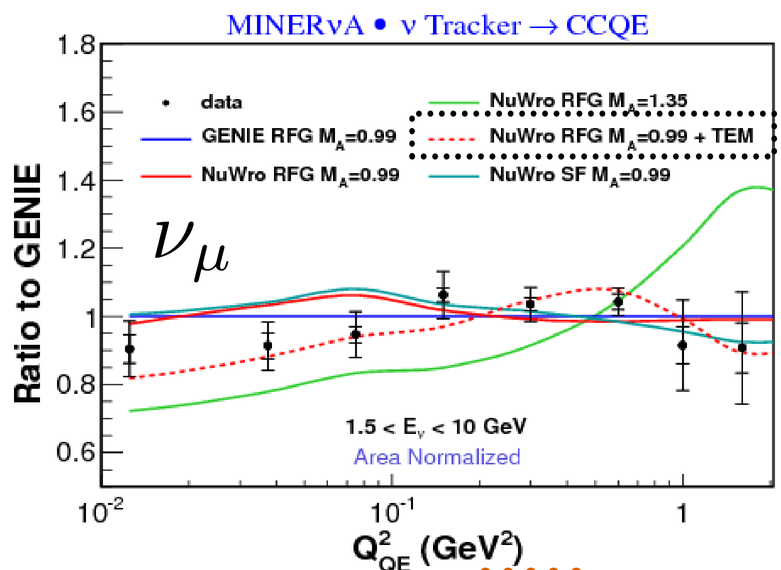
MINERvA: Single Muon QE-like Analysis

Emphasis on the Shape

- Using leptonic information only, the results favor the RFG with $M_A = 0.99$ + a Transverse Enhancement Model for NN correlations (vector current only contributions!!)



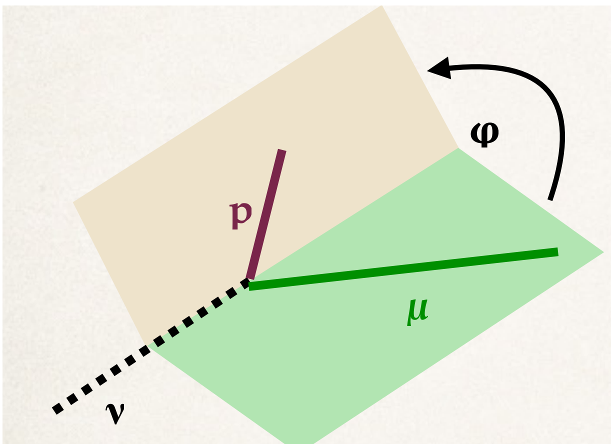
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99



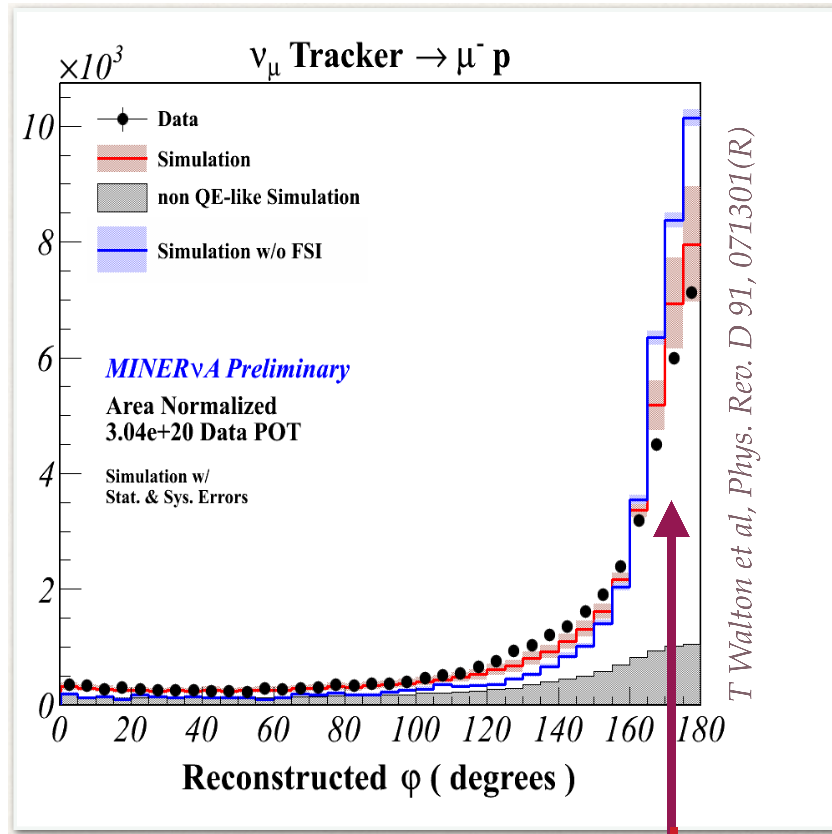
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

Quasi Elastic from the Hadron Side

- Study the angle between the ν-μ and ν-p planes



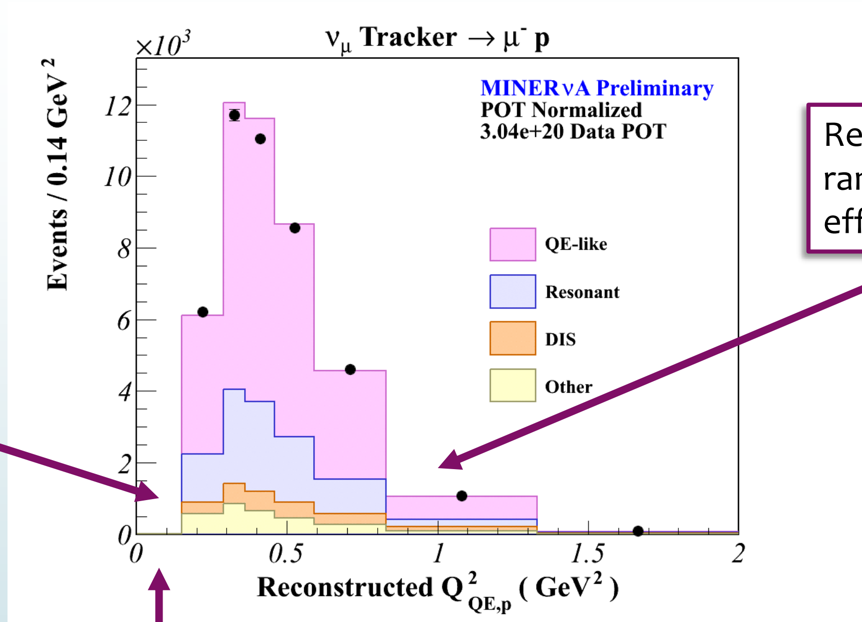
- For QE scattering from a stationary neutron φ should be 180°
- Fermi motion, FSI and QE-like resonant events cause the spread in the distribution.



Data event distribution tends to lower co-planarity angle due to un-modeled FSI, or nuclear correlation effects?

What initial interactions comes out of the nucleus a QE-like event – according to GENIE!

Data Candidates = 40,102



Resonant Production with a pion in the final state dominant background.

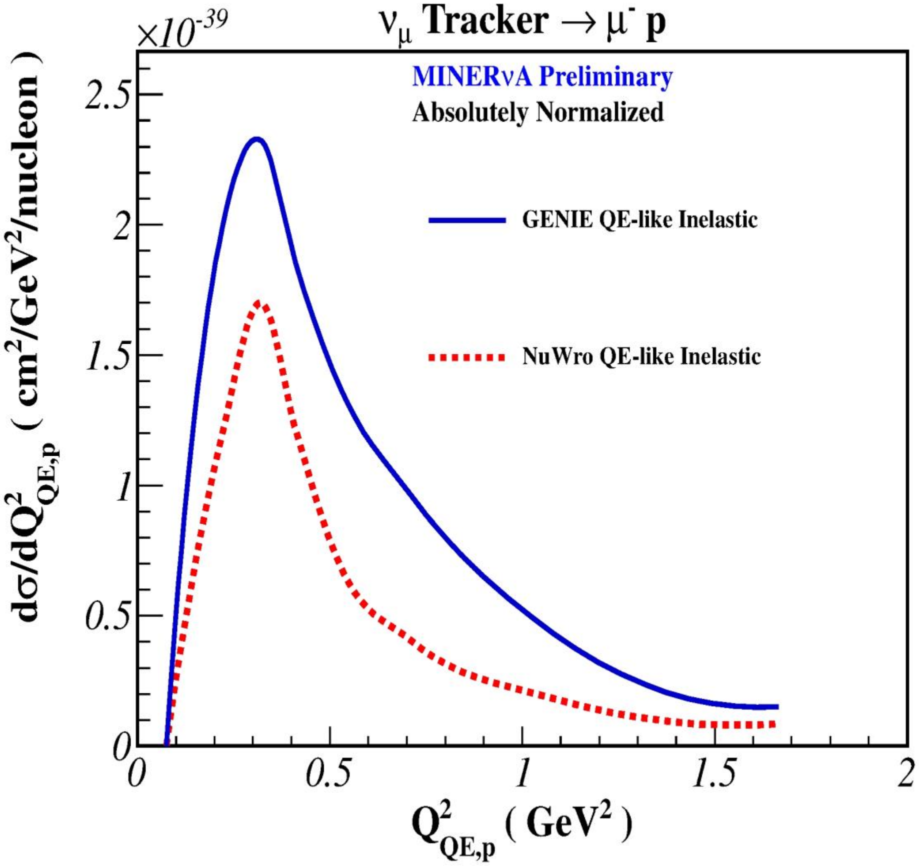
Requiring the hadron to resemble a ranging out proton ⟶ drop in the efficiency.

Tracking threshold prevents the reconstruction of events in the first bin.

The QE-like signal is predicted to consists of:

QE = 72.3 %
Res = 23.9%
DIS = 3.8%

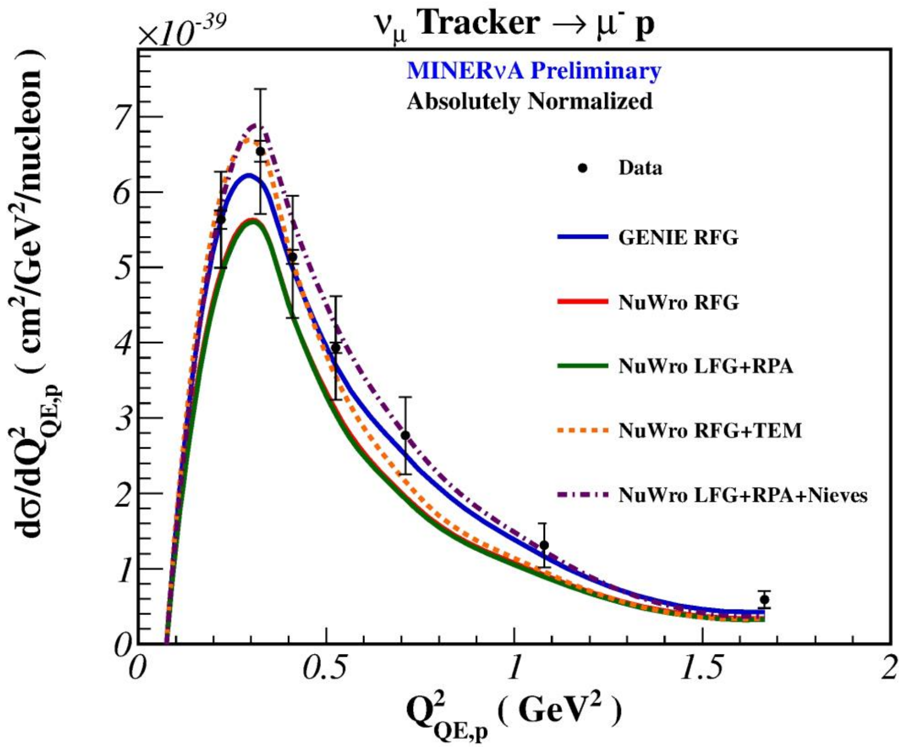
QE-like background

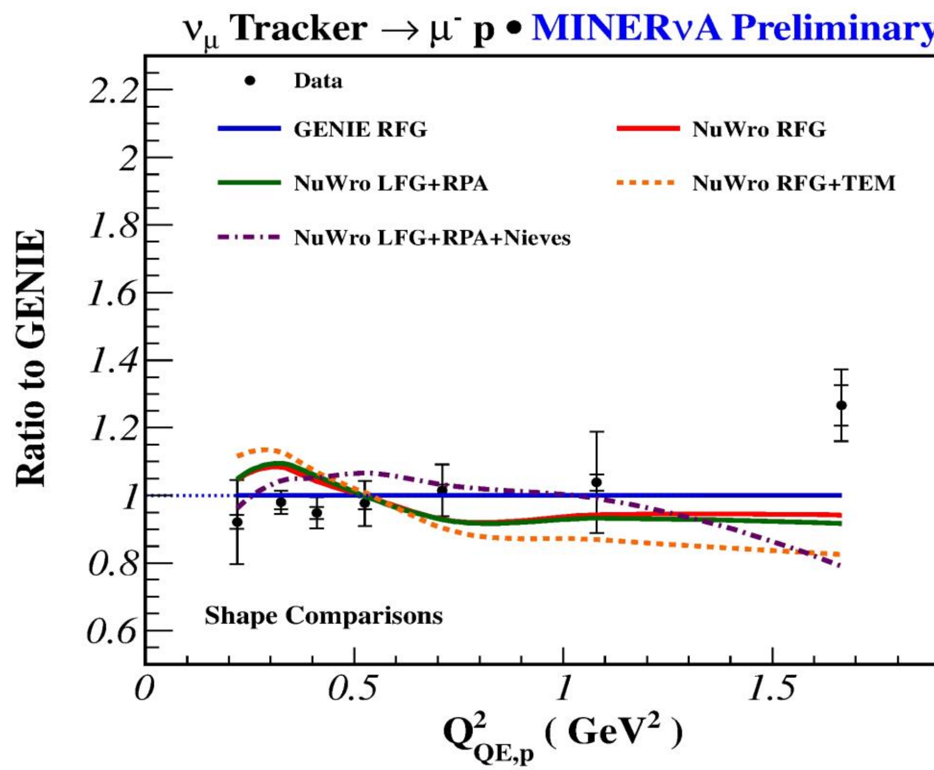


- The major background to true QE events comes from ineleastic produced events detected as QE-like.
- Observe the difference in this inelastic contribution from the NuWro vs GENIE generators!
- Difference in both magnitude and shape coming from modeling of the production cross sections and final state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

Quasi Elastic from the Hadron Vertex

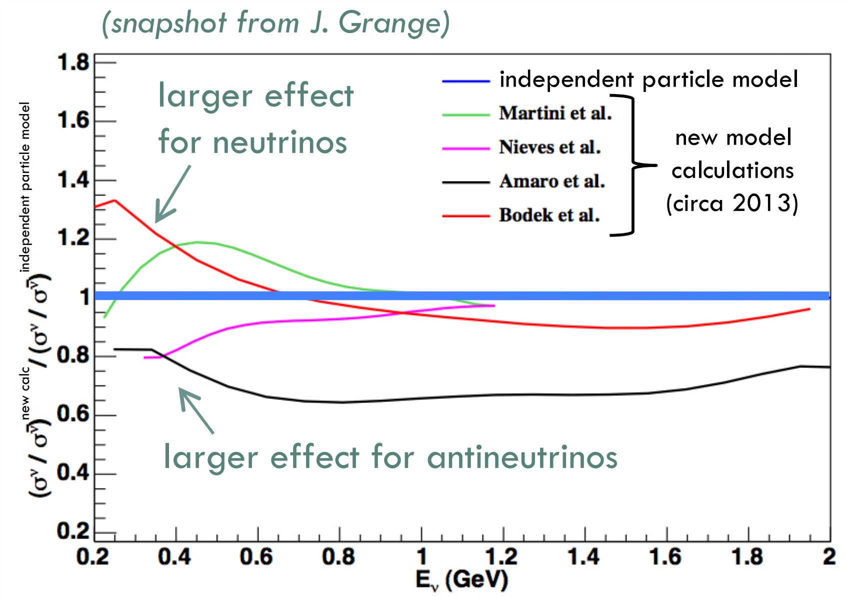
$$Q^2_{QE,p} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$





- Quasi-elastic analysis from the hadron vertex (proton) favors the straightforward GENIE RFG model.
- **This in contrast to the RFG + transverse enhanced model for the analysis from the single muon anlysis - inconsistent**.

ν to $\bar{\nu}$ QE Ratio: Essential for ~~CP~~ studies



- Major differences in the initial ratio of **ν to $\bar{\nu}$** mainly due to different treatments of the axial-vector contribution.
- On top of this comes the many differences of nuclear effects that determine the detected final state topology and energy.
- Consider the large contamination of **ν** in the **$\bar{\nu}$** beam and the need for charge of lepton.
- A challenge for oscillation experiments measuring ~~CP~~

Conclusions: QE-like Scattering off a Nucleus

- Best model fitting single μ QE-like events includes parameterization of N-N correlation effect from e-A scattering (Vector Current Only)

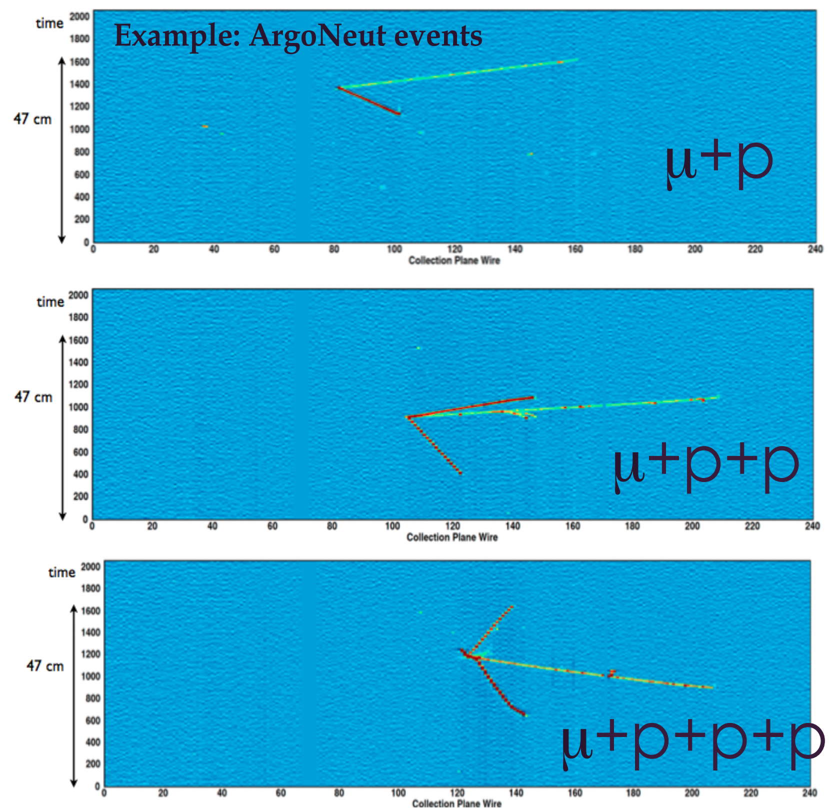
- Best model fitting single μ QE-like events is NOT best for μ + p ! Problem with FSI model?

- **NO SINGLE MODEL FITS MINIBOONE, MINERVA SINGLE μ AND μ + p DATA.**

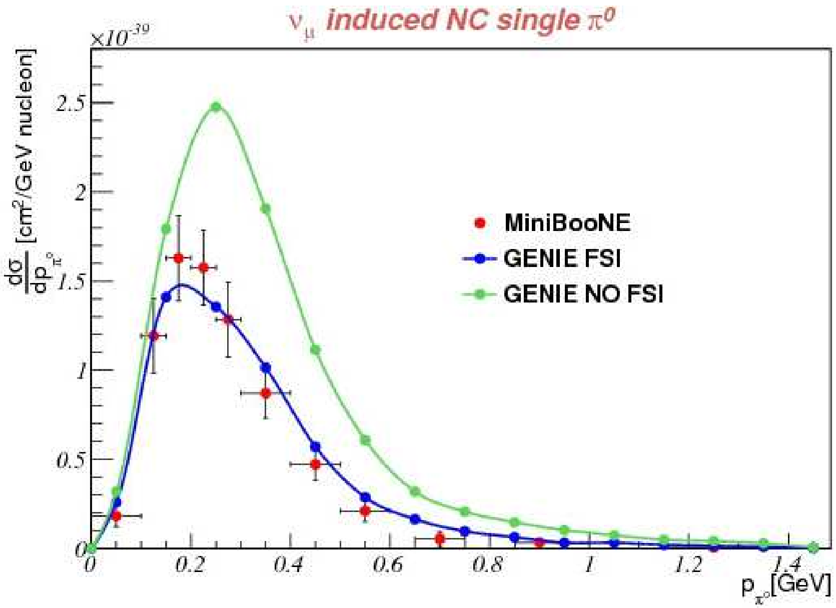
- **Large** variation in predicted ratio of ν to $\overline{\nu}$ cross section ratio.

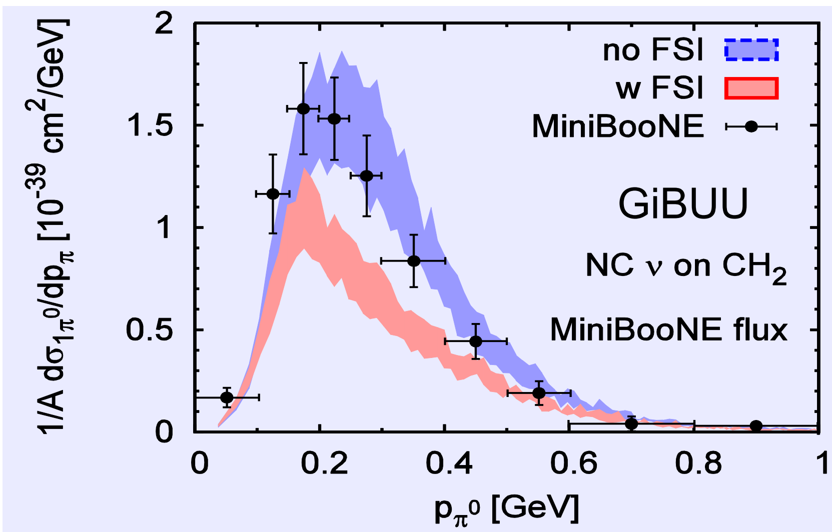
- Evidence for nucleon-nucleon correlations from both MiniBooNE and MINERvA

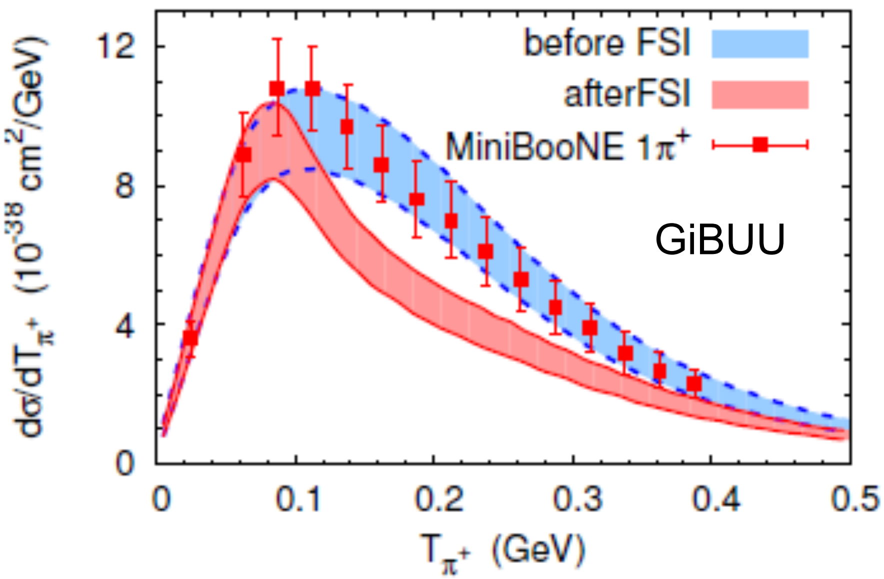
- <u>Waiting for LAr TPC results!</u>



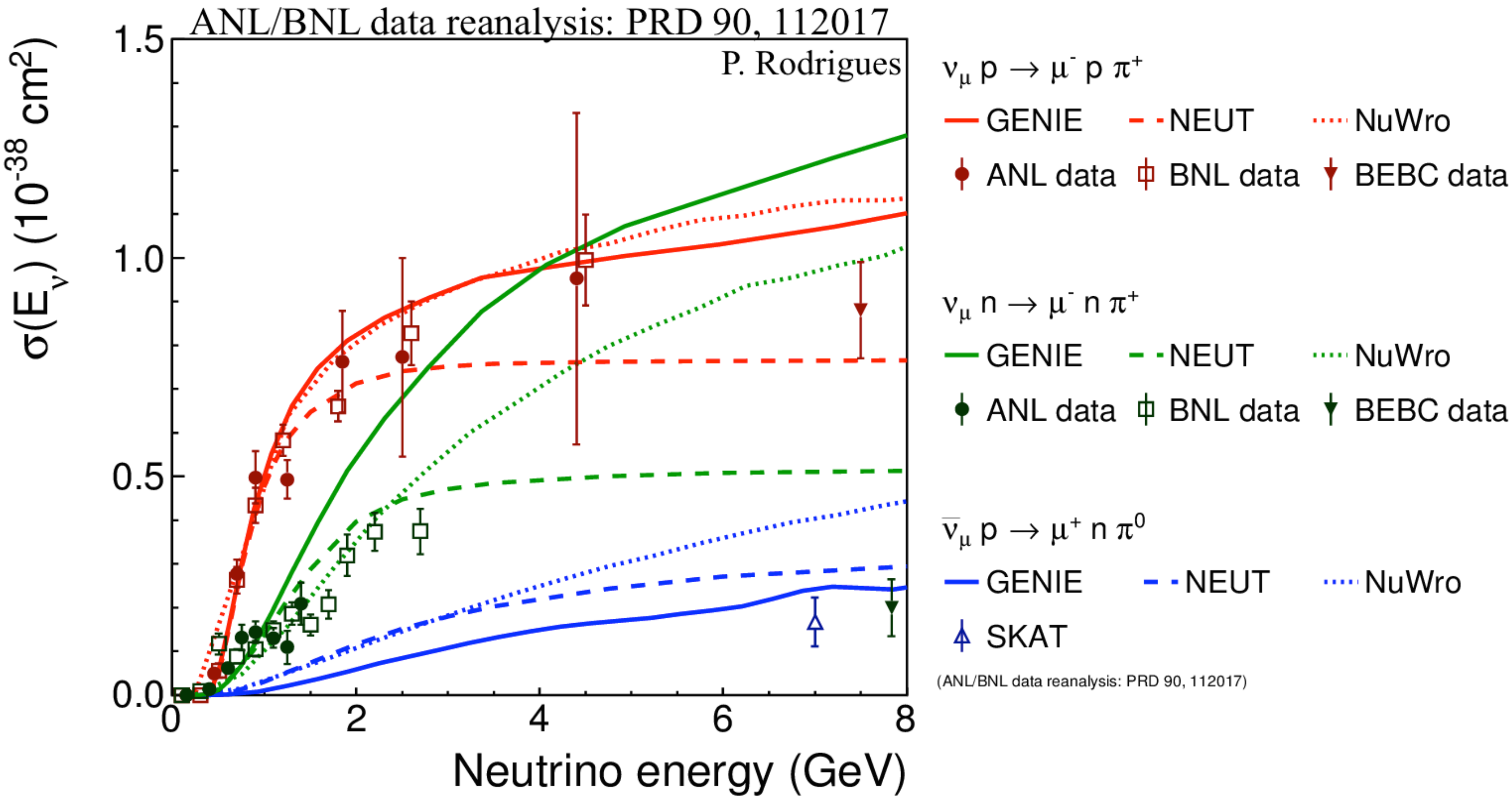
A step up in W to pion production
Comparison of π^0 and $\pi^{\pm}$ Models with Data







What About ν Nucleon → π Cross Sections?



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

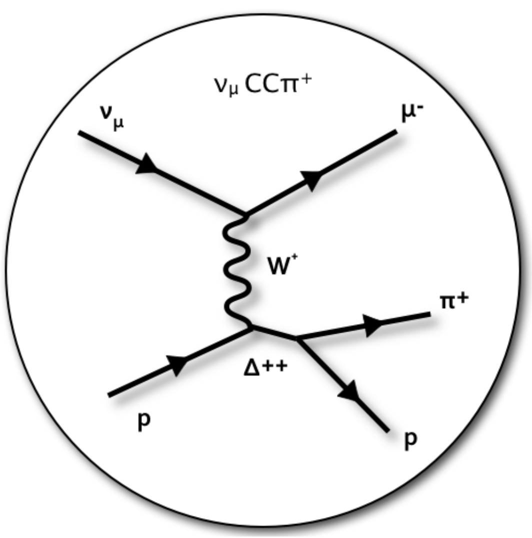
Move up in Hadronic Mass
.MINERvA: Charged and Neutral Pion Analyses

<u>Neutrino</u>

Single charged pion production

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

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

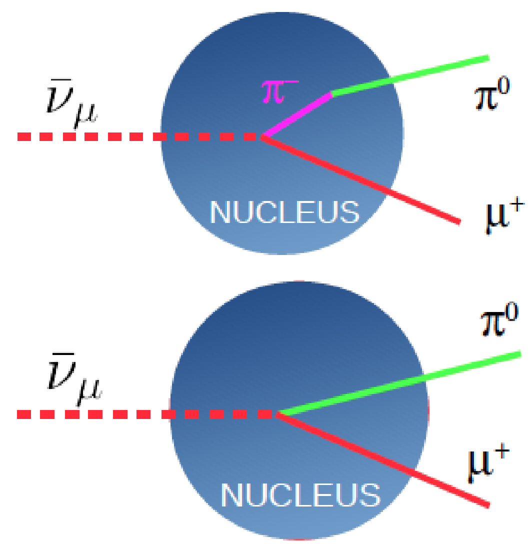


<u>Antineutrino</u>

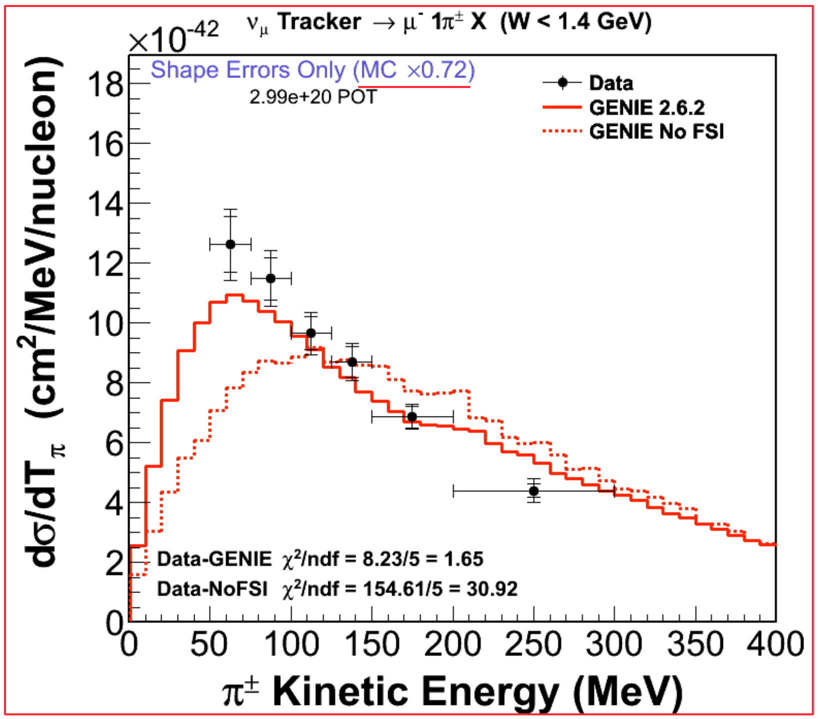
Single neutral pion production

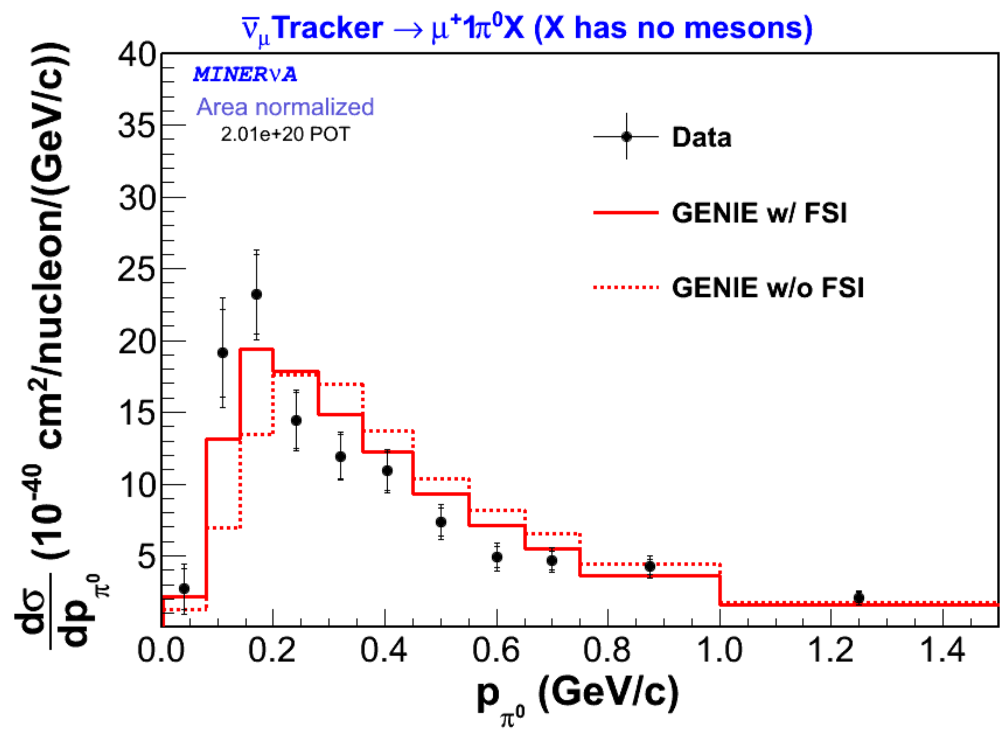
$$\bar{\nu}_\mu + CH \rightarrow \mu^+(1\pi^0)X$$

X contains no mesons



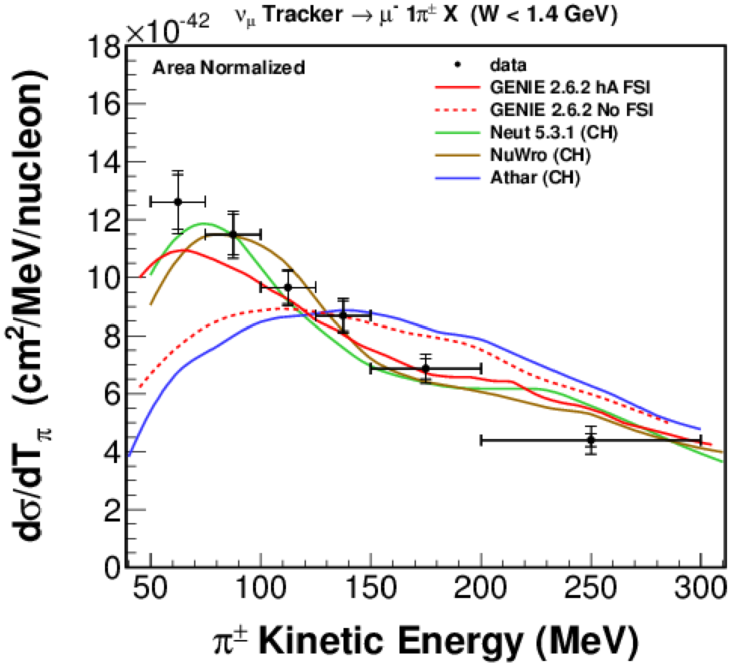
FSI Conclusions for Pion Energy
(Shape Comparisons)

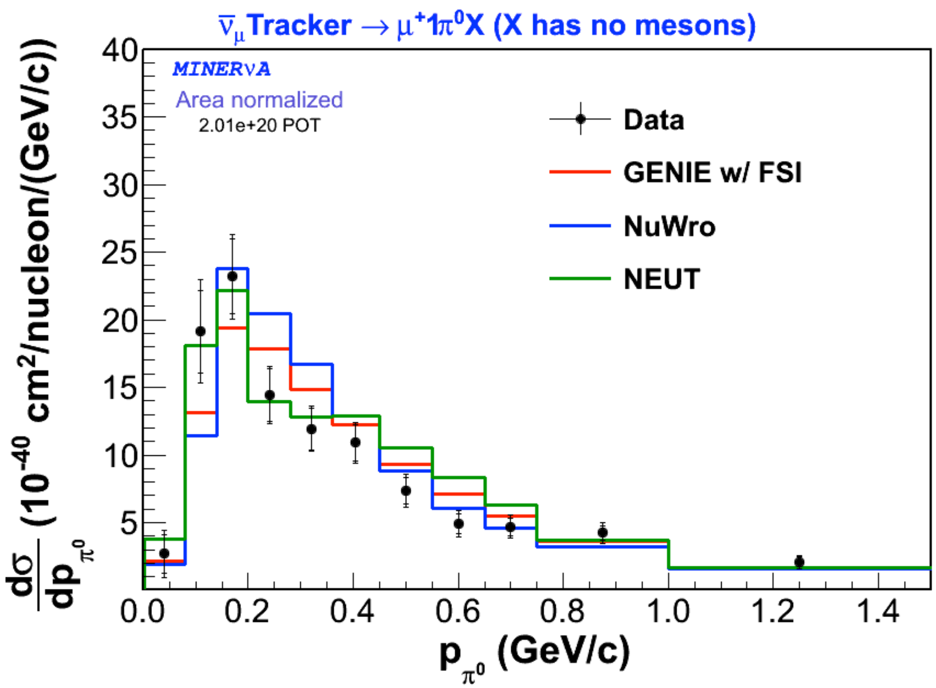




- Data prefer GENIE with FSI

FSI Conclusions for Pion Energy
(Multi model - Shape Comparisons)

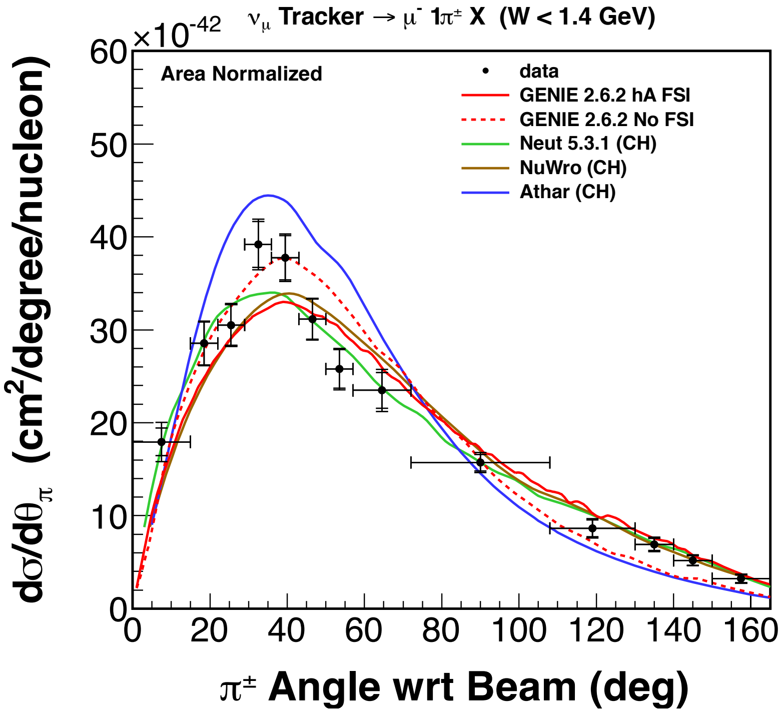


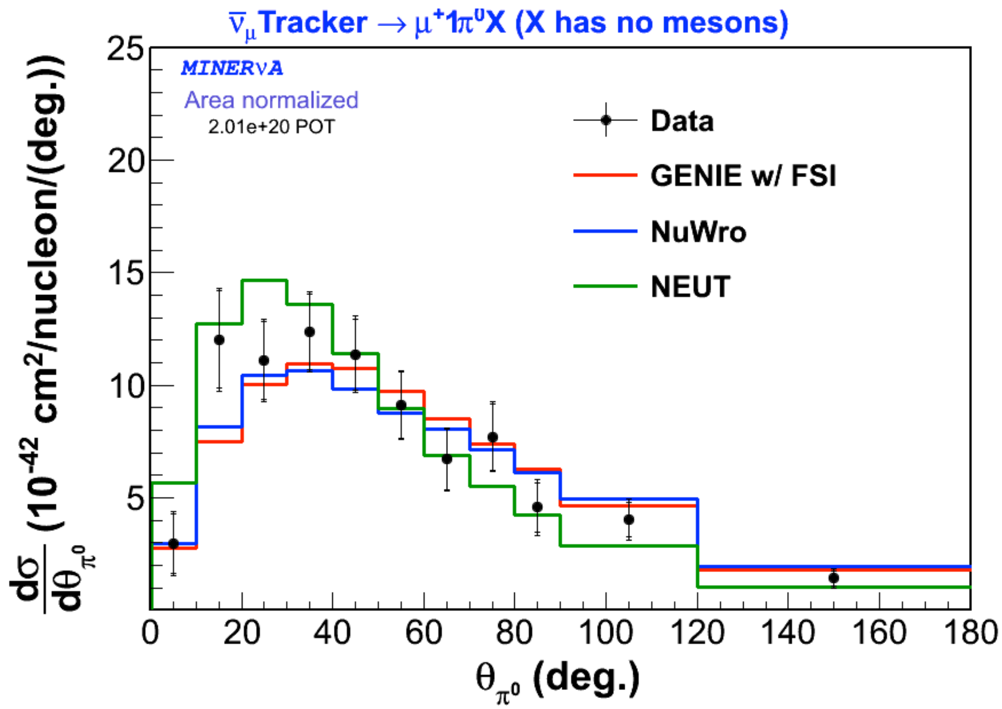


- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Data is unable to distinguish different FSI models

FSI Conclusions for Pion Angle

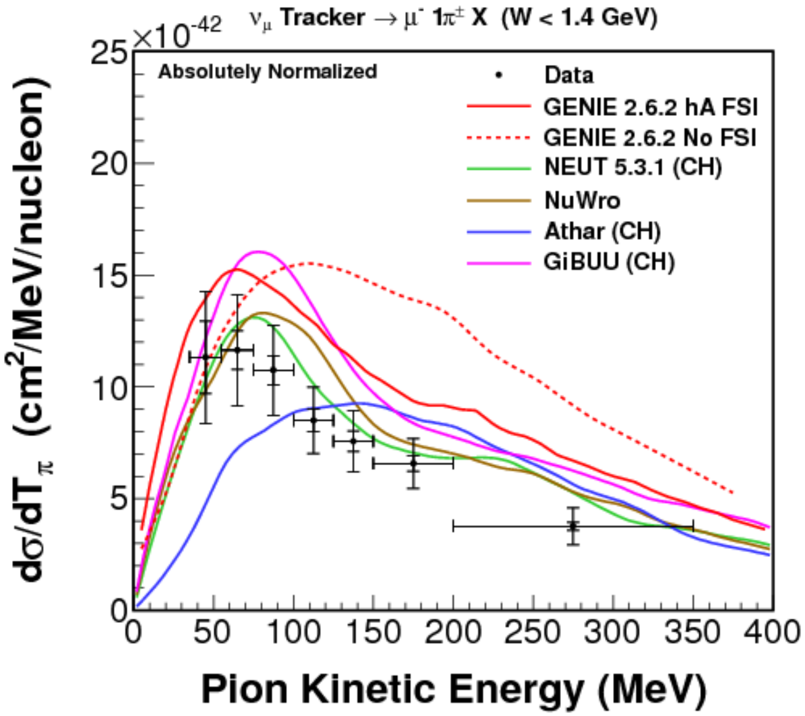
(Multi model - Shape Comparisons)

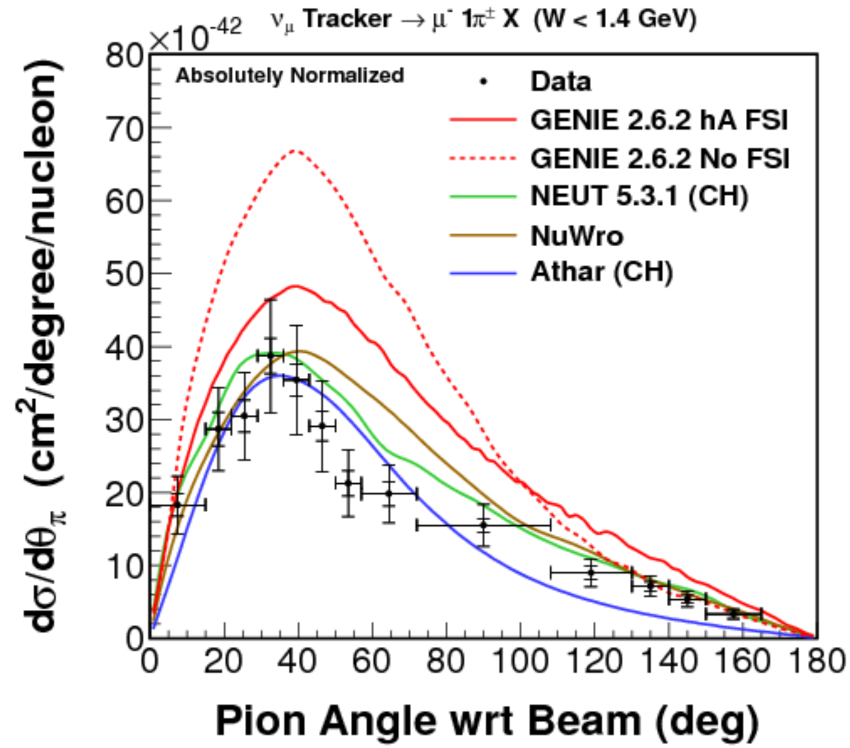




- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Again, data is unable to distinguish different FSI models

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

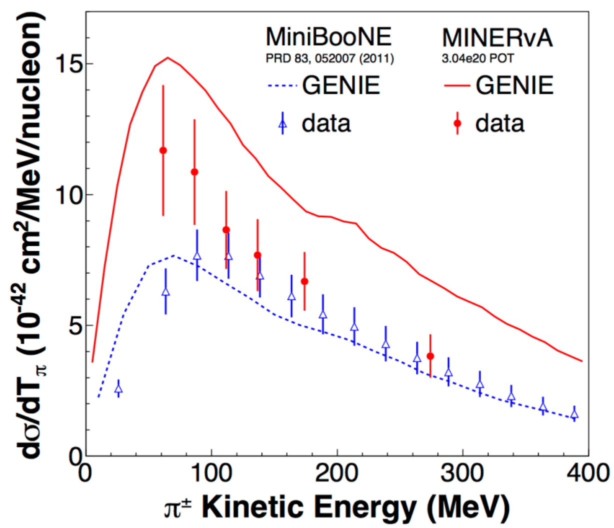




- NEUT and NuWro normalization agree the best with data.
- GiBUU, GENIE normalizations disfavored by a couple σ
- GENIE (with FSI), NEUT, and NuWro predict the data shape well
- Except for Athar, data is unable to distinguish different FSI models

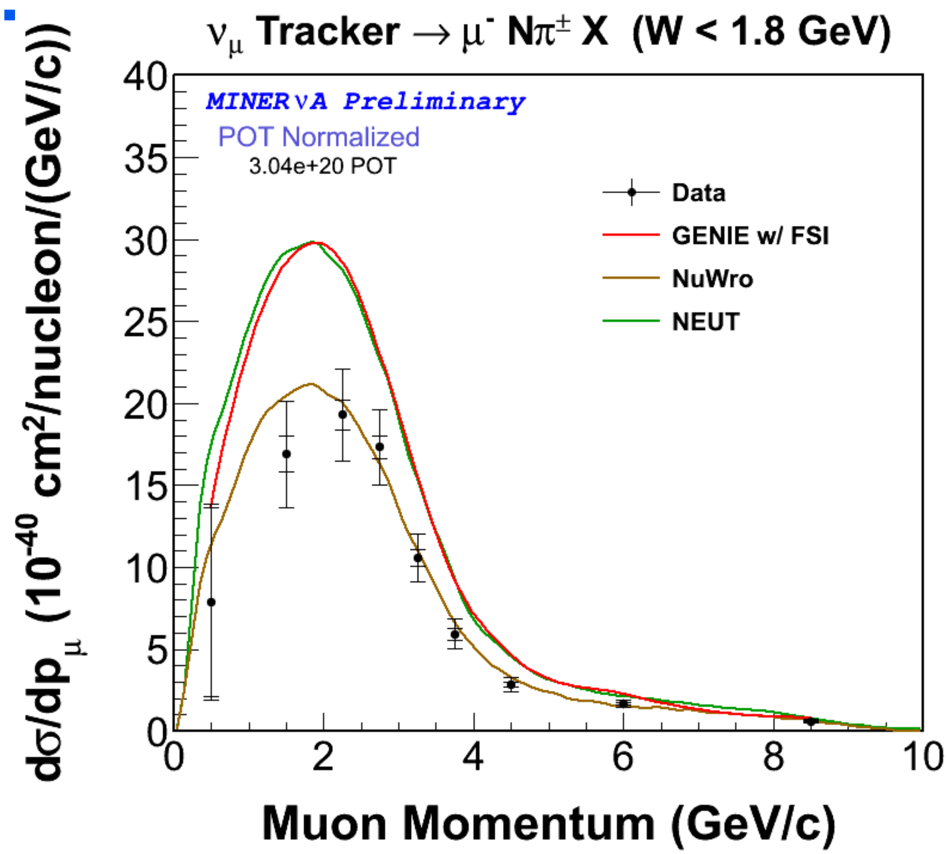
Summary for W < 1.4 GeV Analysis

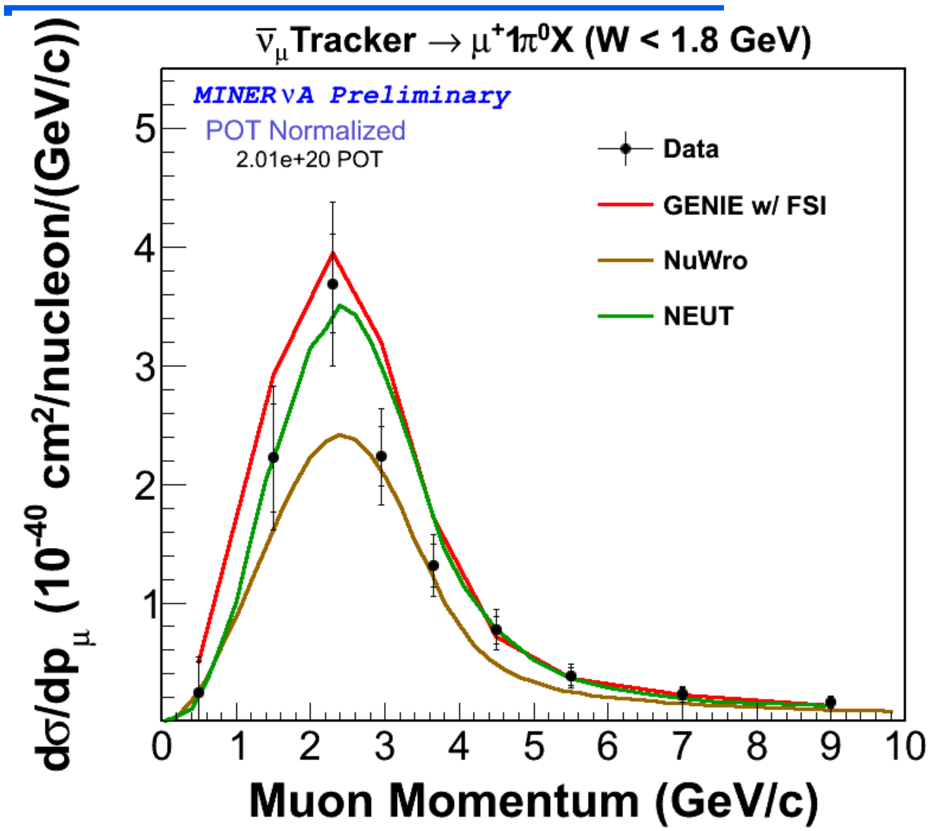
- MiniBooNE - E_ν~1 GeV
  - Best theory models (GiBUU, Valencia) strongly disagree in shape
  - Event generators have shape right, but problems in detail
- MINERvA - $\langle E_\nu \rangle$ = 4 GeV
  - Dominantly Δ resonance formation, decay in nucleus, very similar to MiniBooNE)
  - Event generators 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.

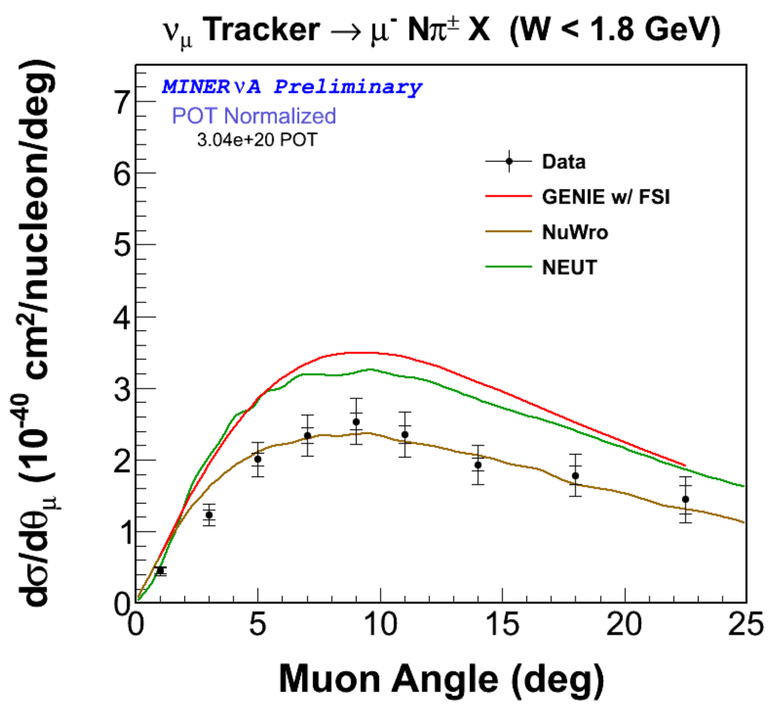
Up into the multi-π zone (W < 1.8 GeV) from the lepton side: Cross section model comparisons for μ momentum

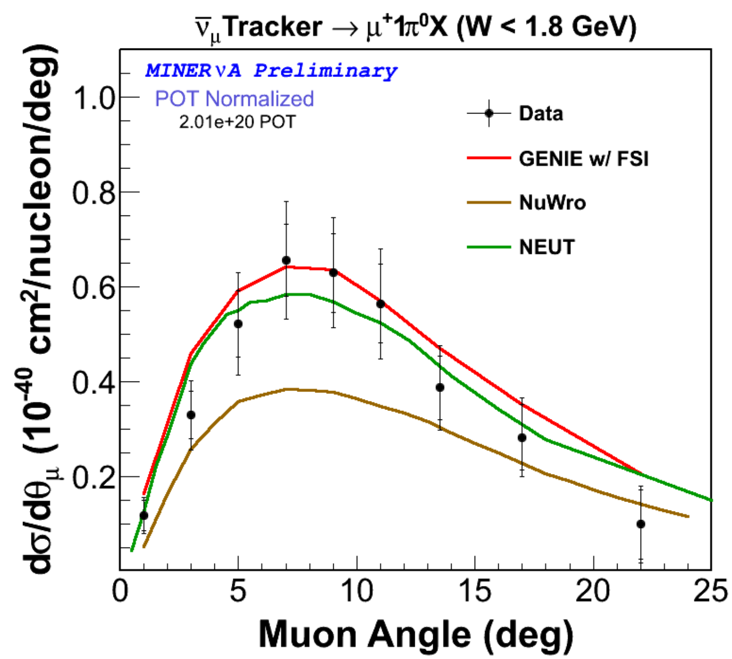




- In charged pion both GENIE and NEUT overestimate the cross section
- GENIE and NEUT predictions are similar and are higher than NuWro in both analyses

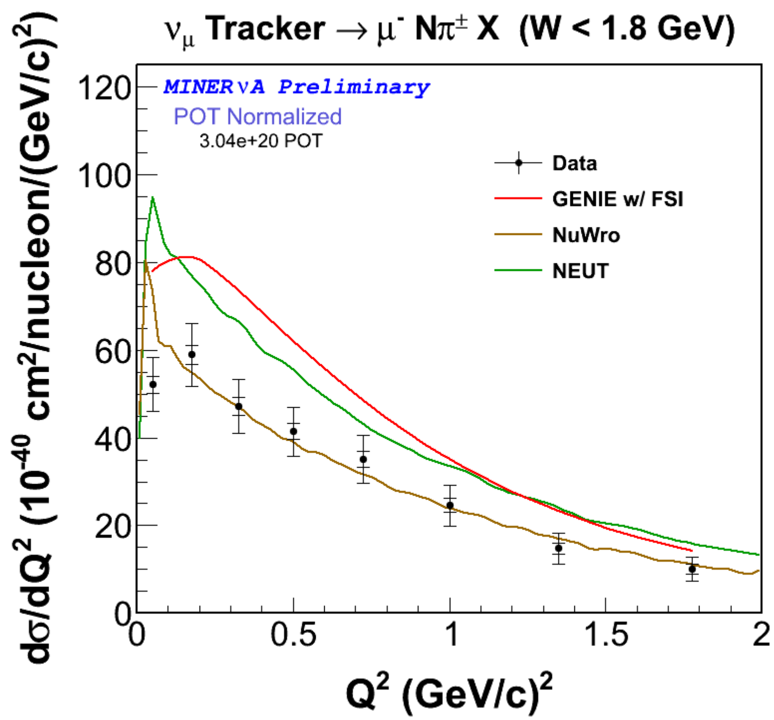
Up into the multi-π zone (W < 1.8 GeV) from the lepton side: Cross section model comparisons for μ angle

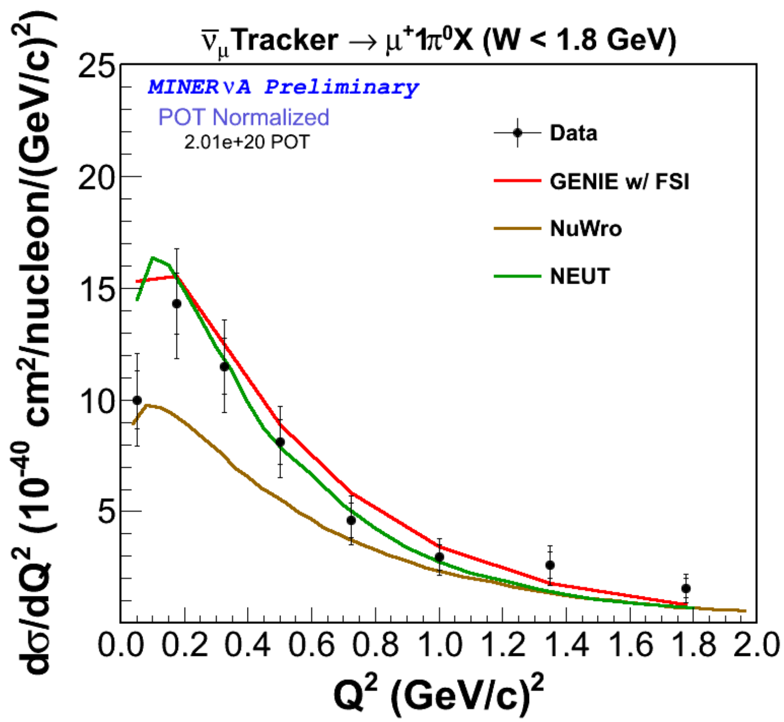




- The same normalization and shape behavior as with the μ mometum

Up into the multi-π zone (W < 1.8 GeV) from the lepton side: Cross section model comparisons for Q^2





- In charged pion both GENIE and NEUT over estimate the cross section (as in the muon variables)
- In the shape analysis, GENIE agrees well with data except in lowest Q^2 bin of the neutral pions.
- In lowest Q^2 bin of the charged pions, coherent production in NuWro & NEUT

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

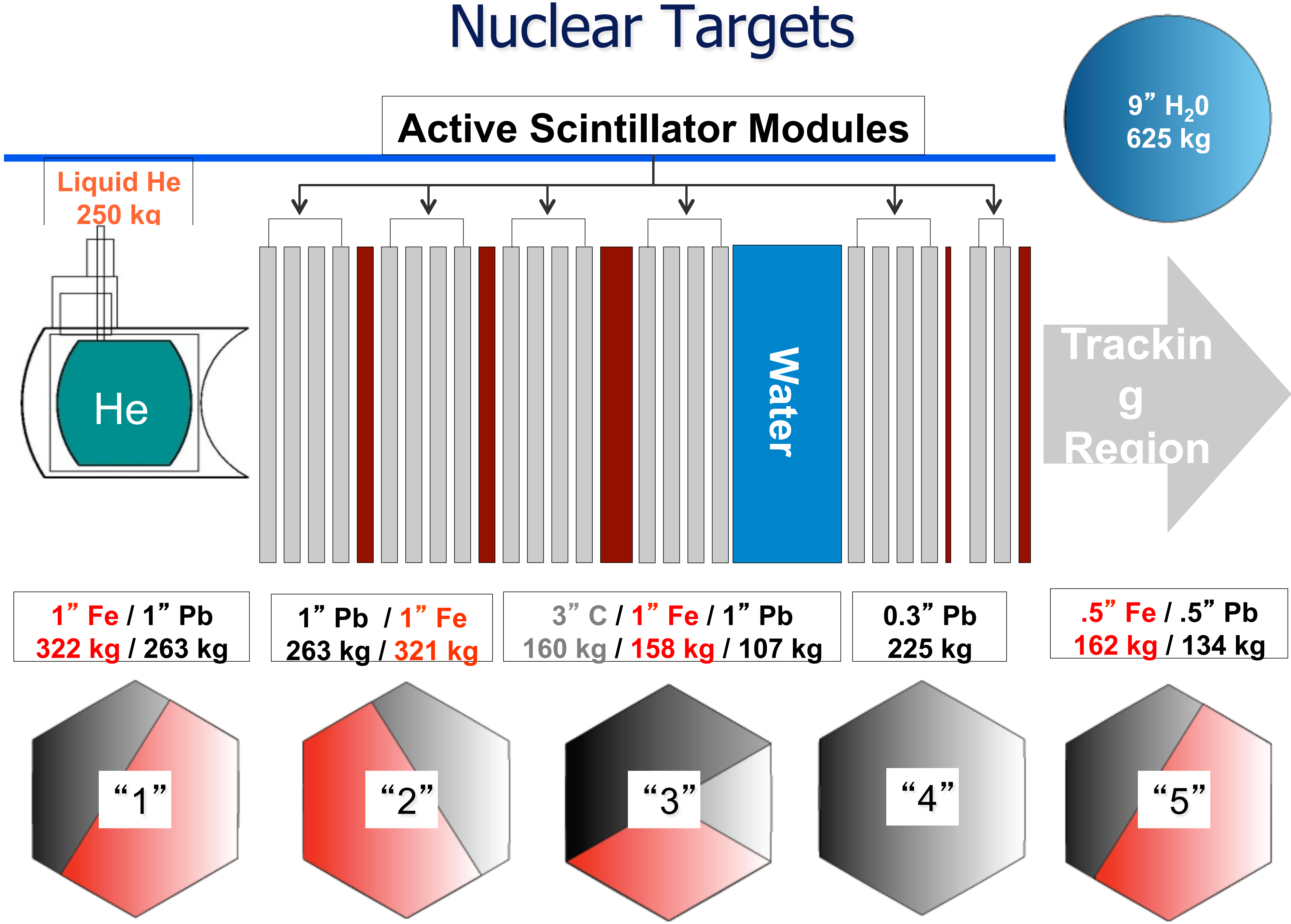
- Distributions of the muon observables (p_μ, θ_μ, E_ν, Q^2) are sensitive to nuclear structure.

- 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!**

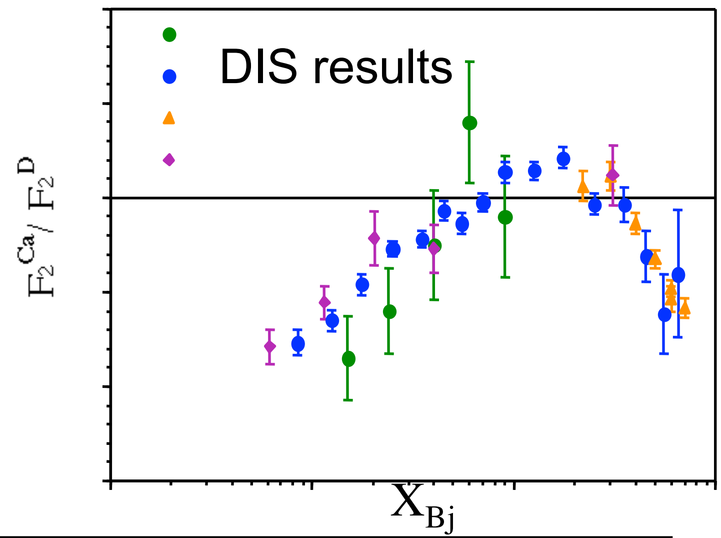
Nuclear Targets



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.
- This has been measured for **DIS events**



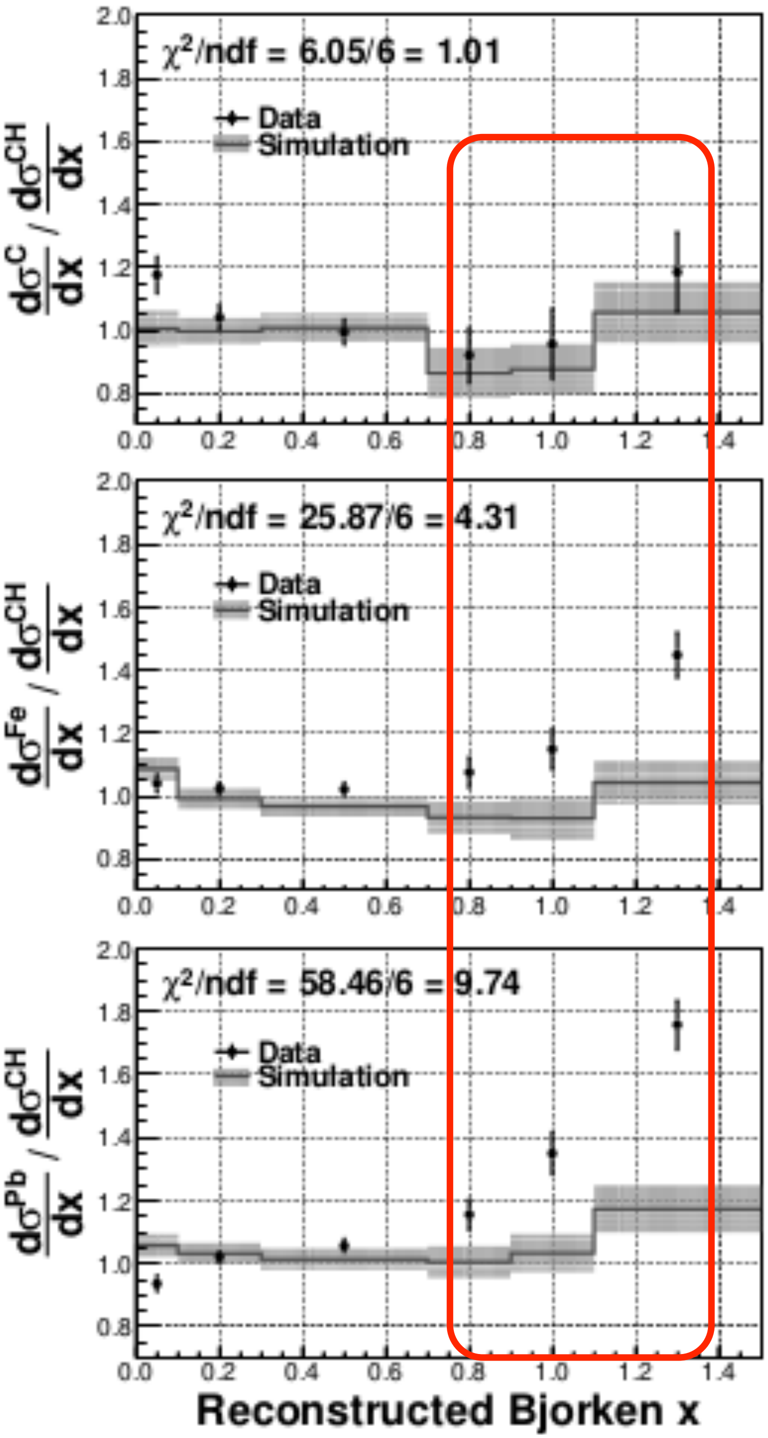
Reconstructed x MINERvA	QE (%)	Res (%)	DIS (%)	lowQ DIS (%)	Con (%)	Mean Generated Q^2 (GeV^2)
0.0–0.1	11.3	42.5	5.9	19.2	15.7	0.23
0.1–0.3	13.6	36.4	16.7	9.1	23.0	0.70
0.3–0.7	32.7	32.8	11.8	1.4	21.1	1.00
0.7–0.9	55.1	25.4	4.3	0.5	14.6	0.95
0.9–1.1	62.7	21.6	2.8	0.5	12.3	0.90
1.1–1.5	69.6	18.1	1.9	0.4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

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%



Low x summary
INCLUSIVE RATIOS

- At x = [0.0,0.1], we observe a **deficit** that increases with the size of the nucleus. This effect is not modeled in the simulation.
- Expected Neutrino Differences in shdowing
  - Neutrino sensitive to xF_3.
  - Axial-vector current has a different coherence length.

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%
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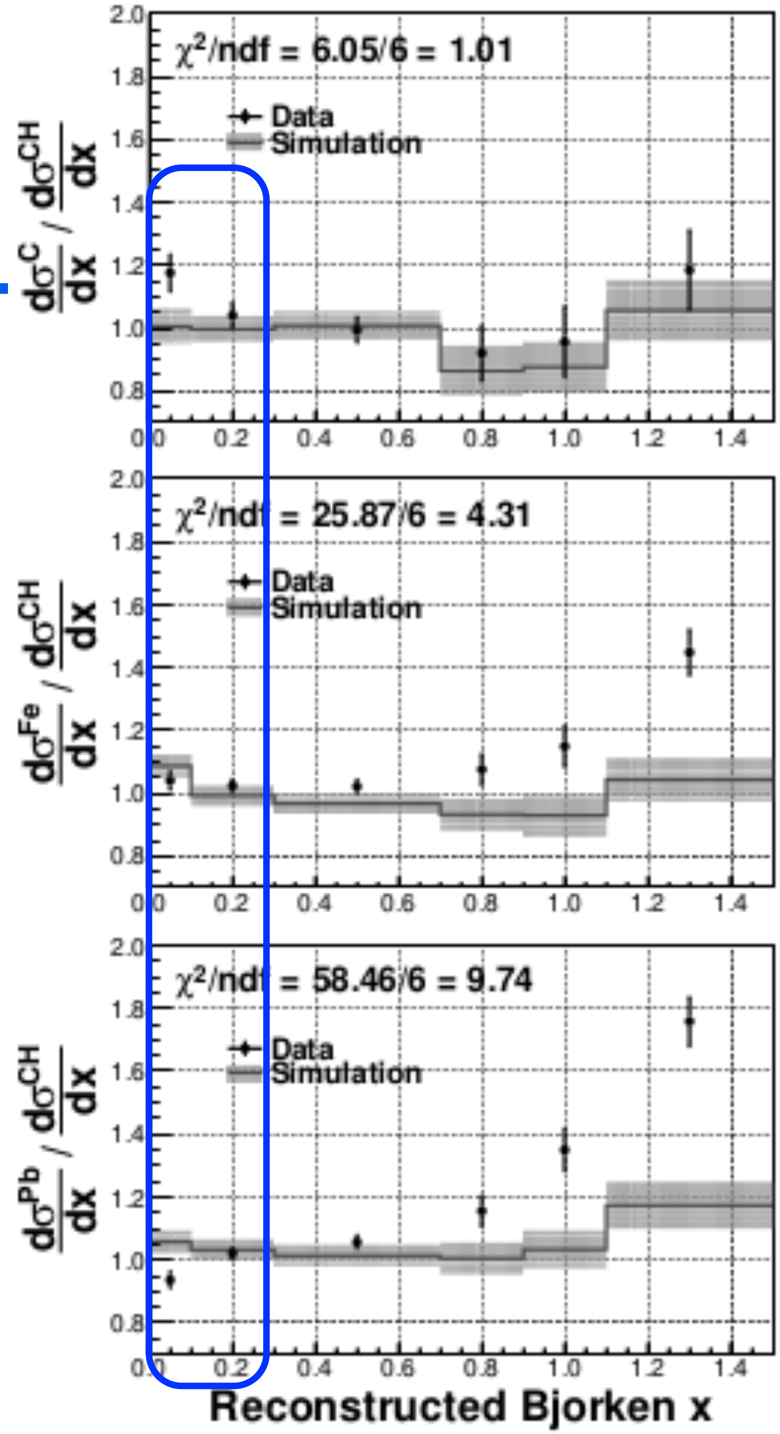
1.1 – 1.5	69.9%	1.9%	28.4%
> 1.5	79.1%	0.6%	20.2%



ν – A Deep Inelastic Scattering at MINERνA

Probing Nucleon Structure in Nuclei with Neutrinos

Neutrinos – weak probe of nuclear (low Q) and hadronic (high Q) structure

ν probes same quark flavors as charged leptons but with different "weights"

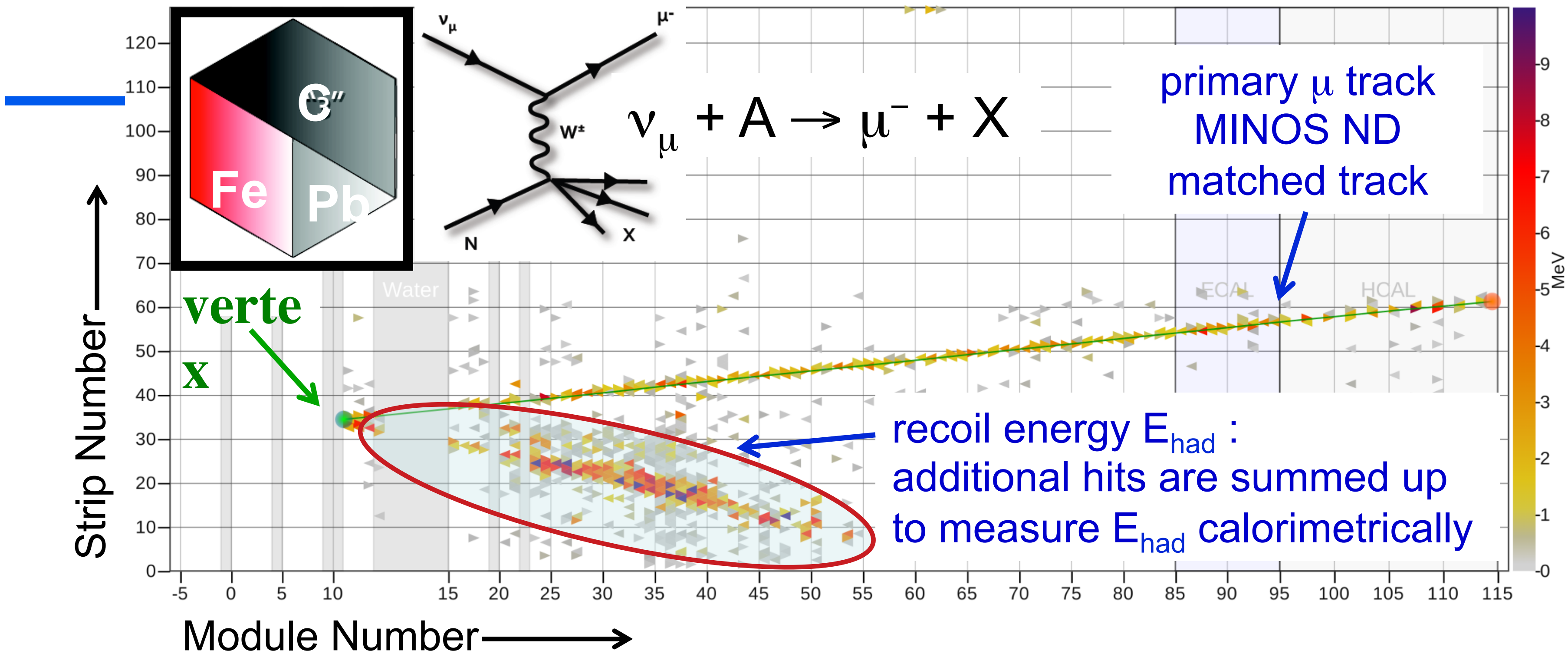
ν's also sensitive to the axial piece of F_2 and xF_3

- → expect different shape ?
- → expect different behavior ?
- → $x \to 1$?
- → is shadowing the same ?

Nuclear effects in neutrino (DIS) scattering are not well established, and have not been measured directly. Most DIS experimental results to date have involved one target material per experiment such as Fe or Pb.

MINERνA attempts a systematic study of these effects using different A targets in the same detector exposed to the same beam

Event Selection and Reconstruction



Event selection criteria:

single muon track in MINERνA, well reconstructed and matched into MINOS ND

“standard cuts”: $2 < E_\nu < 20$ GeV & $\theta_\mu < 17^0$ (MINOS ND acceptance)

CH_2: reconstructed vertex inside fiducial tracker region

nuclear targets: z position of vertex consistent with nuclear target

recoil energy E_{recoil} sum of visible energy, weighted by amount of passive material

$\Rightarrow$ incoming neutrino energy E_ν: $E_\nu = E_\mu + E_{recoil}$

What Have We Observed with EM Probes ?

Charged lepton scattering data show that quark distributions in nucleons bound in a nucleus are modified w.r.t. free nucleons (EMC effect, shadowing at low x, …)

PDFs of a nucleon within a nucleus are different from PDFs of a free nucleon

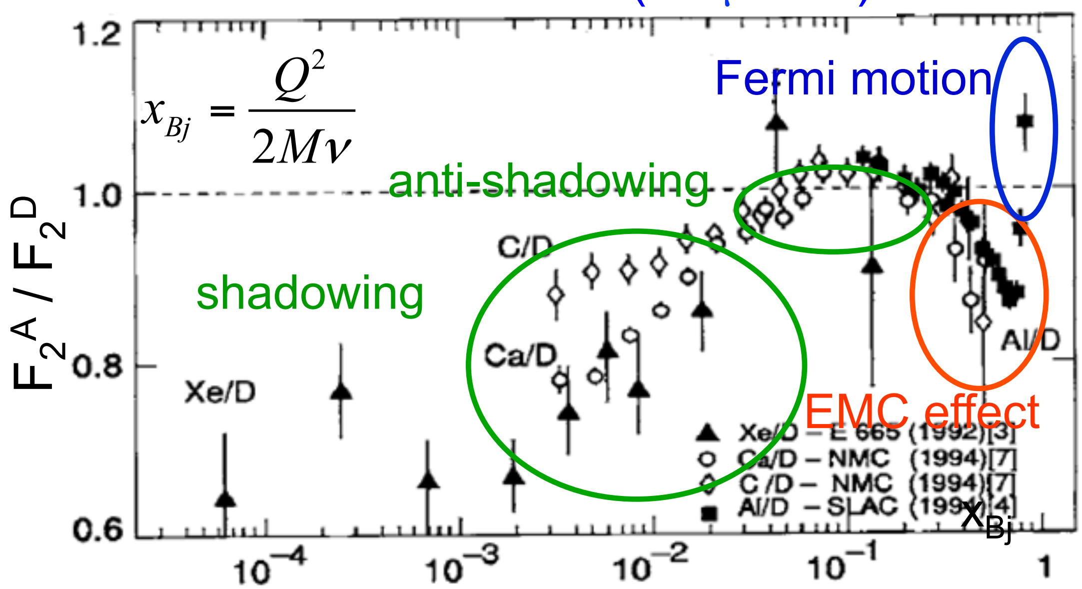
CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years

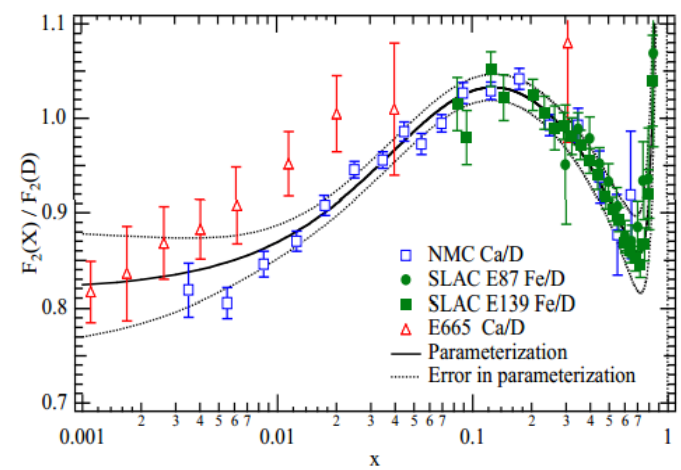
Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

A / D Ratio (e / μ DIS)



The EMC effect (valence region) does not shows a strong A dependence for F_2^A / F_2^D

(Neutrino event generators rely on measurements from charged leptons). With GENIE all nuclei have same modifications. All treated as isoscalar iron.



Nuclear modification fit for iron to deuterium ratio

Attempts to Incorporate the NuTeV data in Global QCD Analysis

Both CTEQ and MRST find this data set "incompatible" with the other data sets in the global analysis—with our usual assumptions;

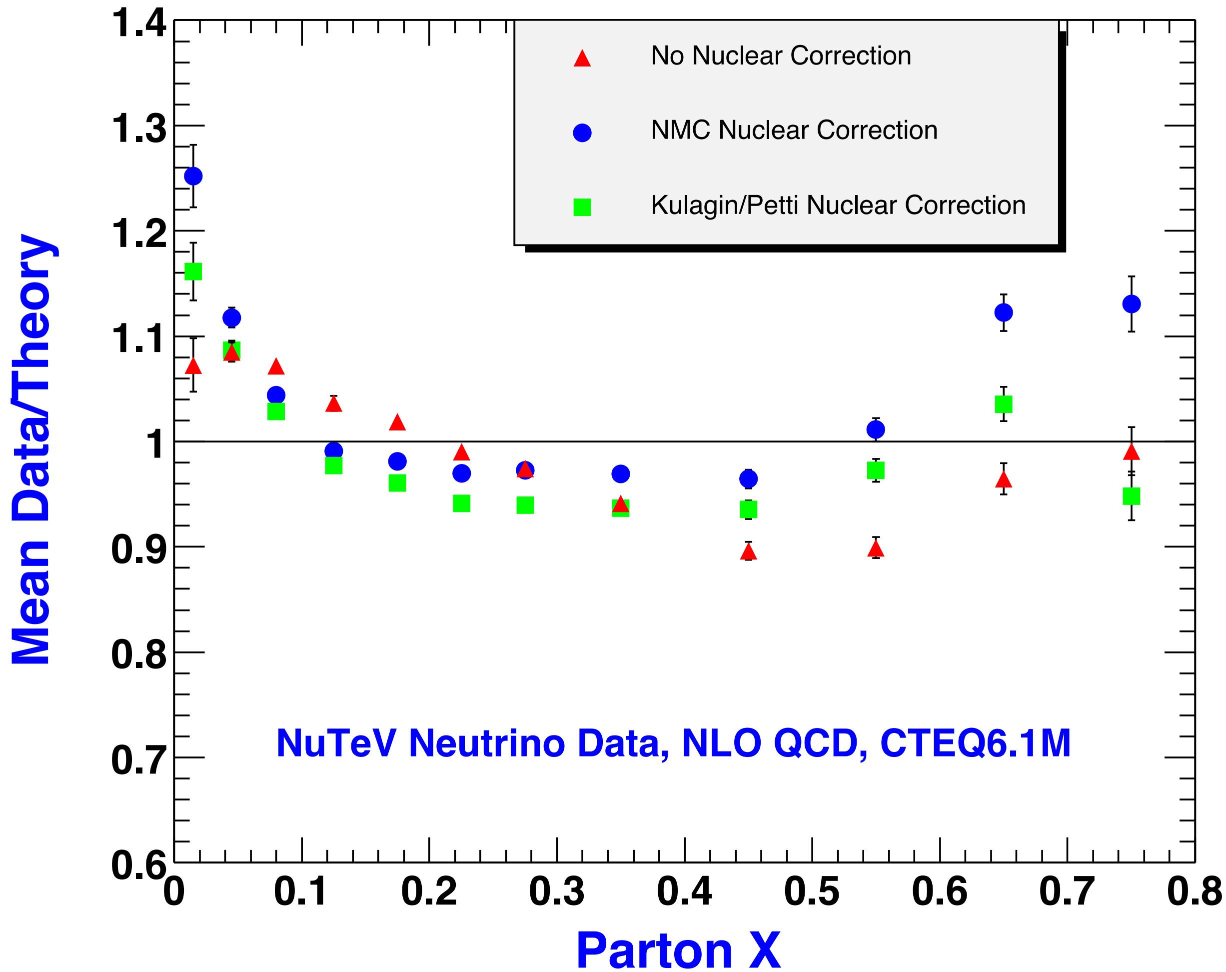
- CTEQ tried to: (i) vary nuclear target corrections; (ii) include target and heavy quark mass effects, …
  None of these help; some make things worse;

- MRST find similar problems: their "best fit" with free parametrization of "nuclear correction factor" **yields unrealistic shape of this factor;**

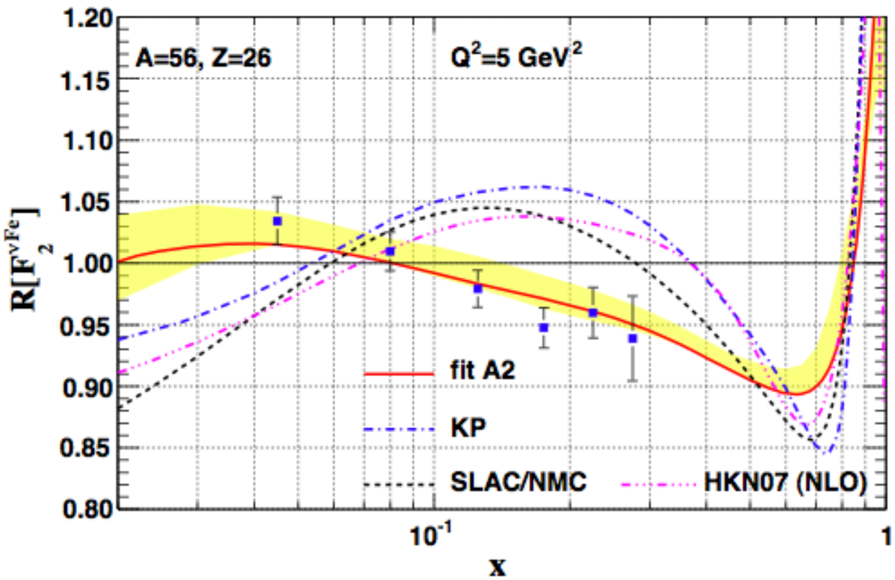
- New CHORUS data agree more with CCFR than with NuTeV;

Can Nuclear Corrections Help? (CTEQ)

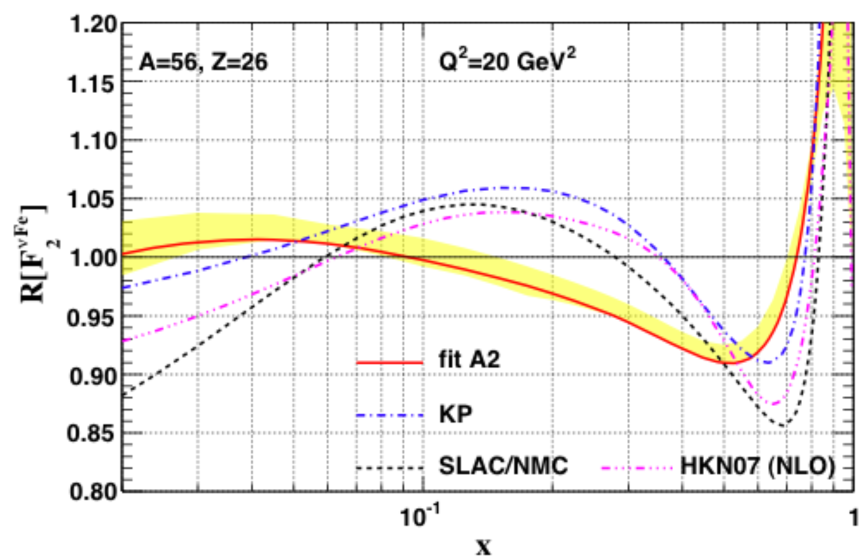
- For each x, data are combined and errors are weighted;
- See a systematic x-dependent deviation that cannot be reduced substantially by any reasonable nuclear correction models.



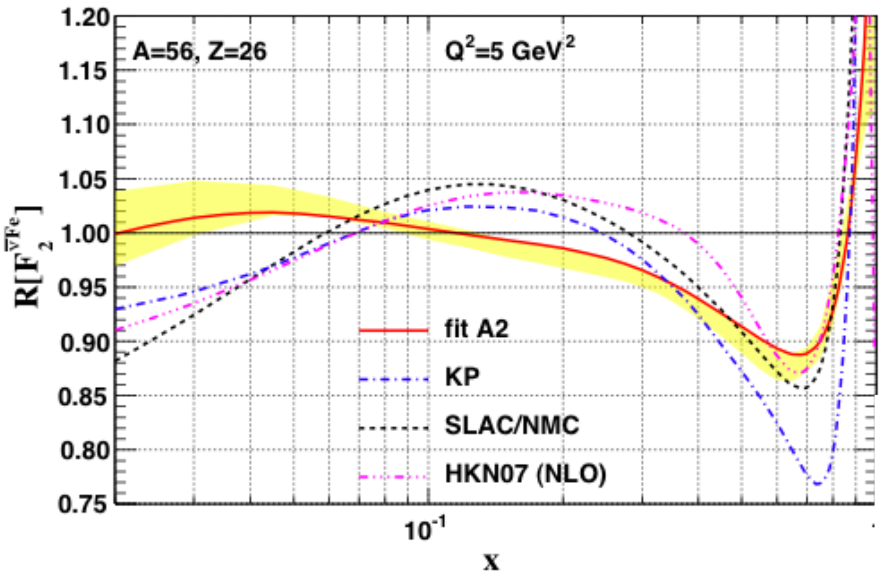
F_2 Structure Function Ratios: ν-Iron



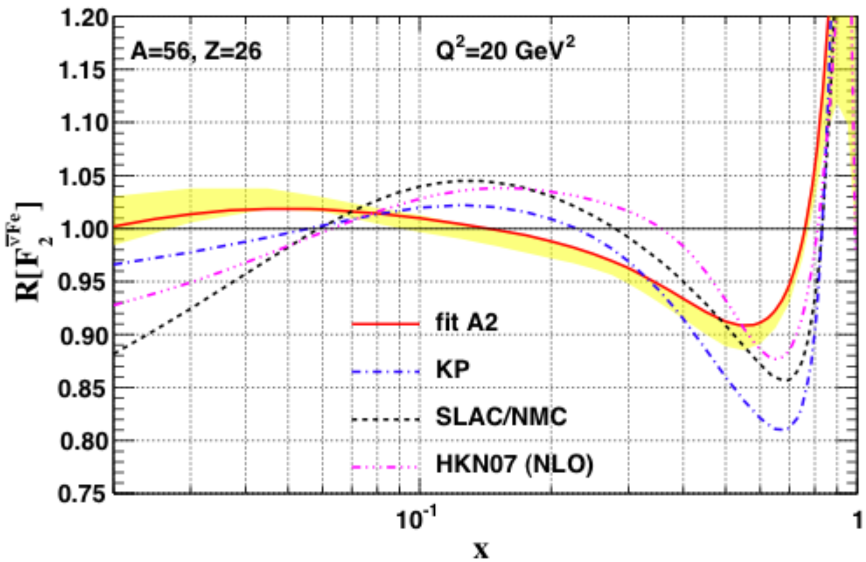
$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



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

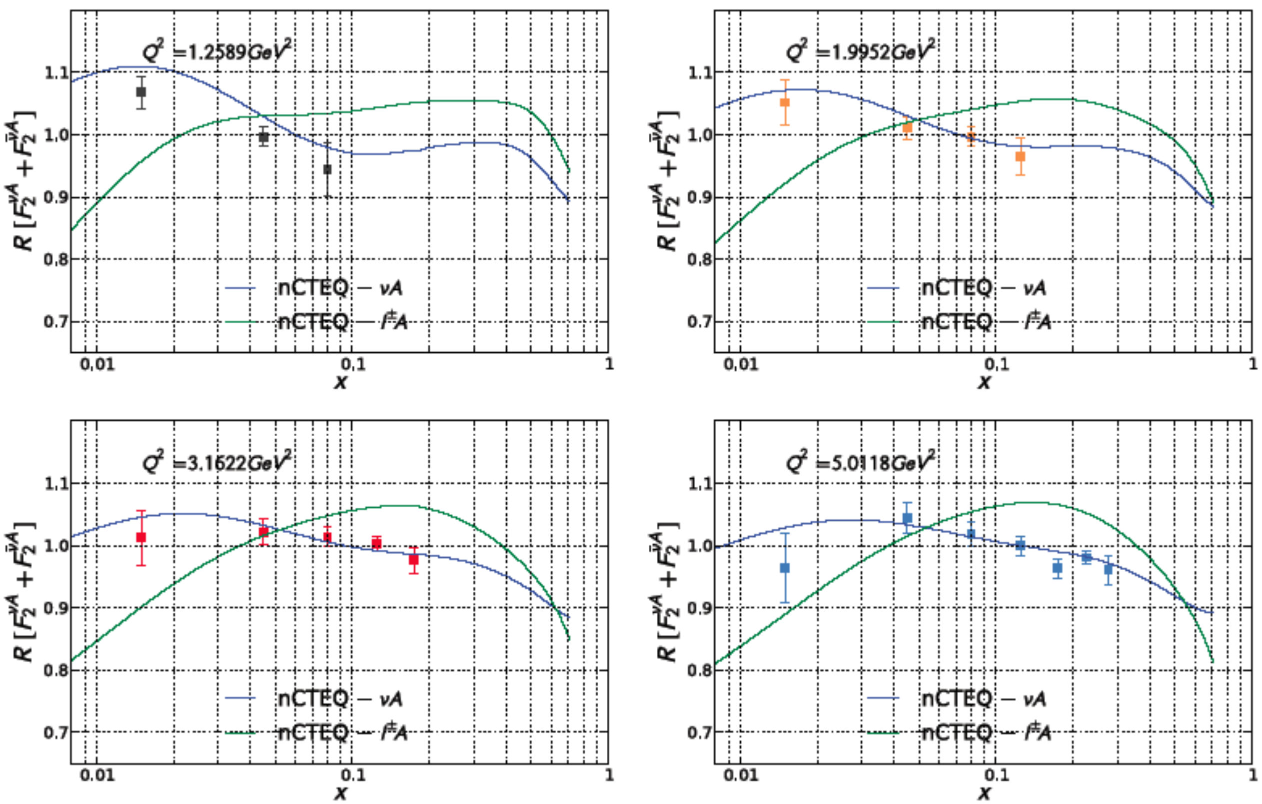


$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



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

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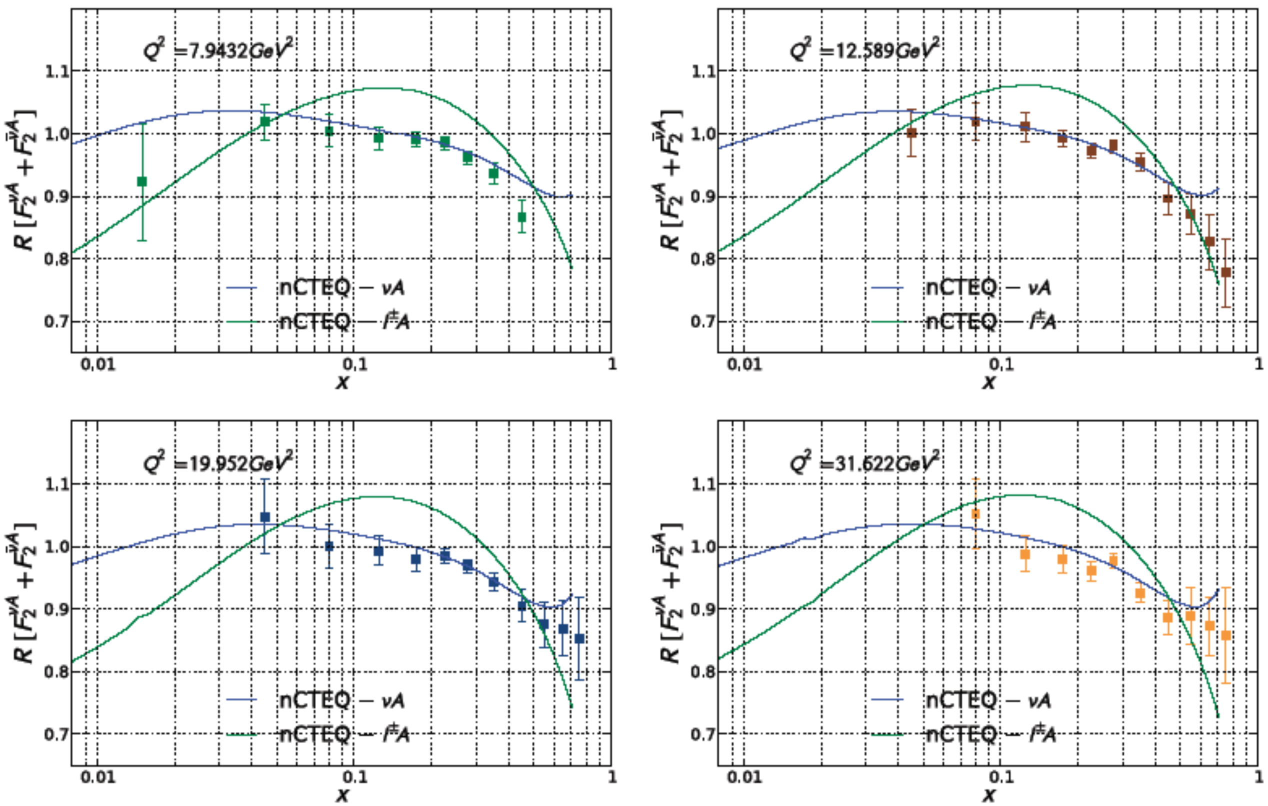


CTEQ Predictions for MINERνA

General strategy has been to adapt electron scattering effects into neutrino scattering theory.

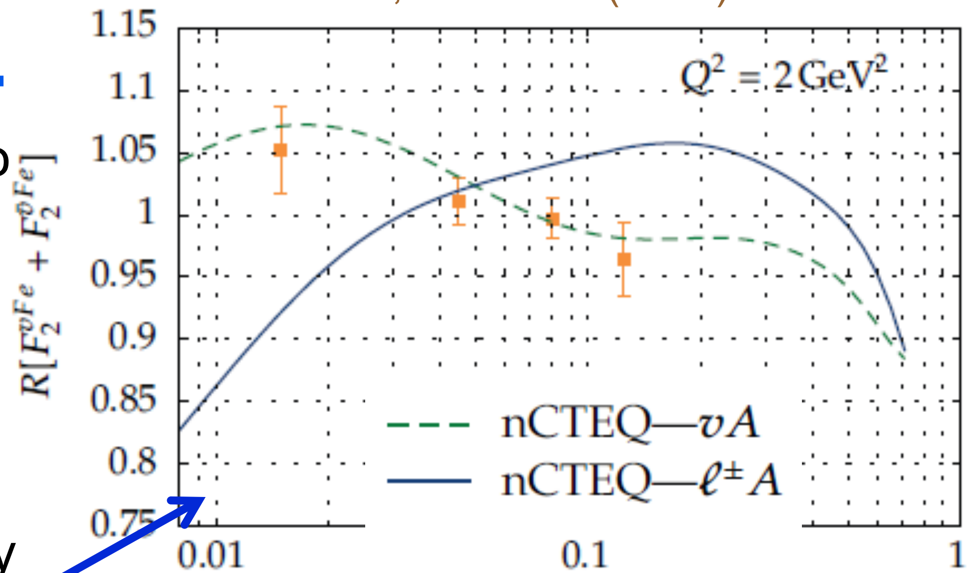
Neutrino event generators rely on measurements from charged leptons

CTEQ fit for neutrino nuclear effects by comparing NuTeV structure functions on iron to predicted "n+p" structure functions.
Compared to predictions from $l^{\pm}$ scattering.

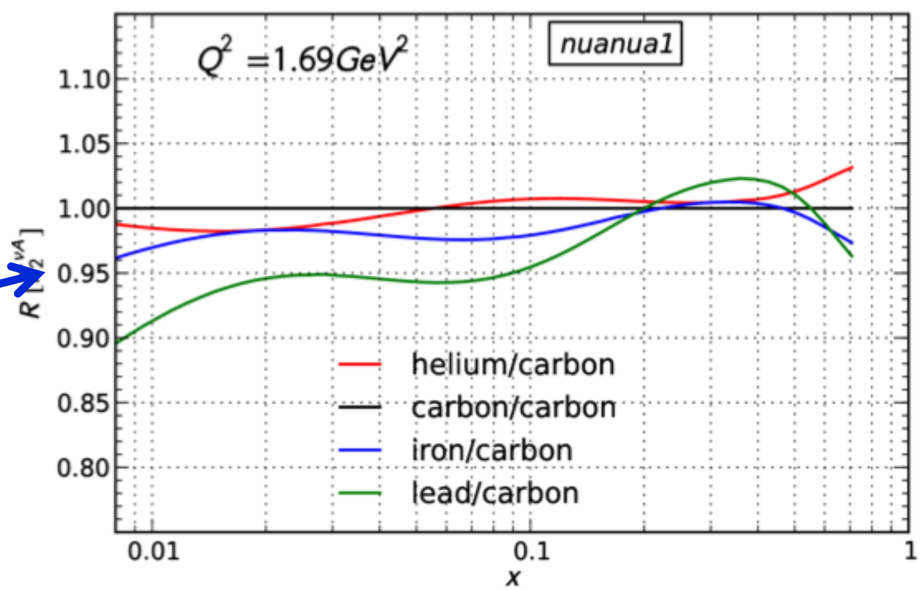
CTEQ prediction for the structure function ratios MINERνA can measure 5% to 10% effects predicted for Pb / C.

Should be also studied using D targets.

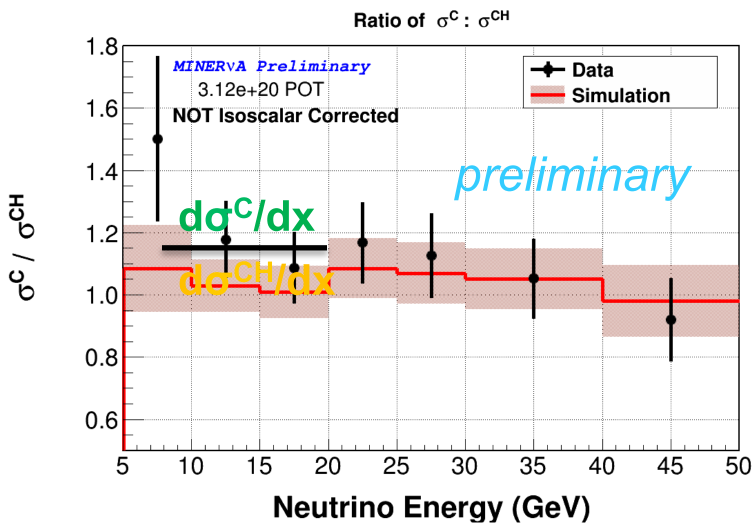
Morfin, Adv. HEP (2012) 934597

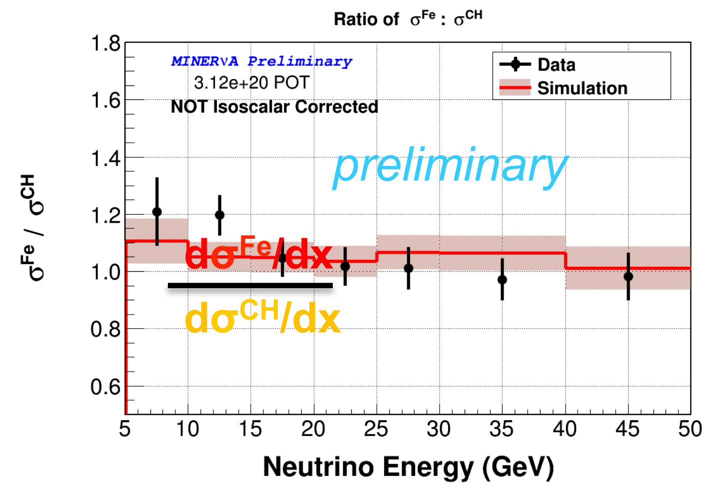


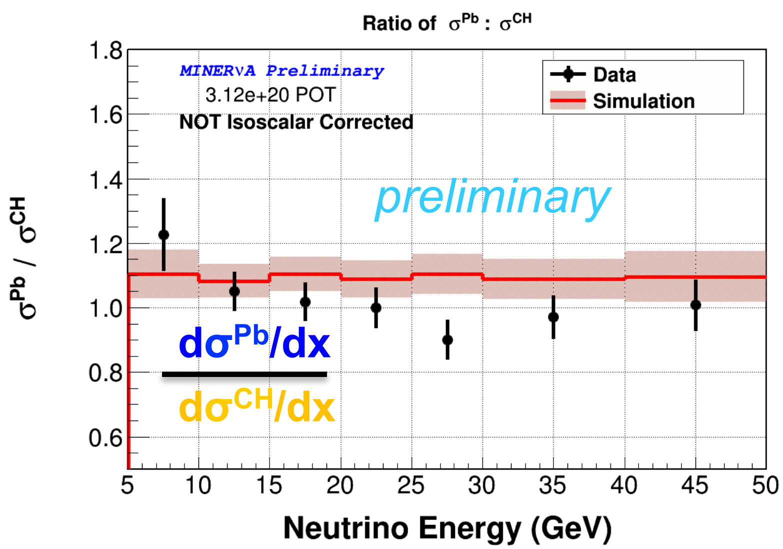
Kovarik PRL106 (2011) 122301



DIS Cross Section Ratios – σ (E_ν)







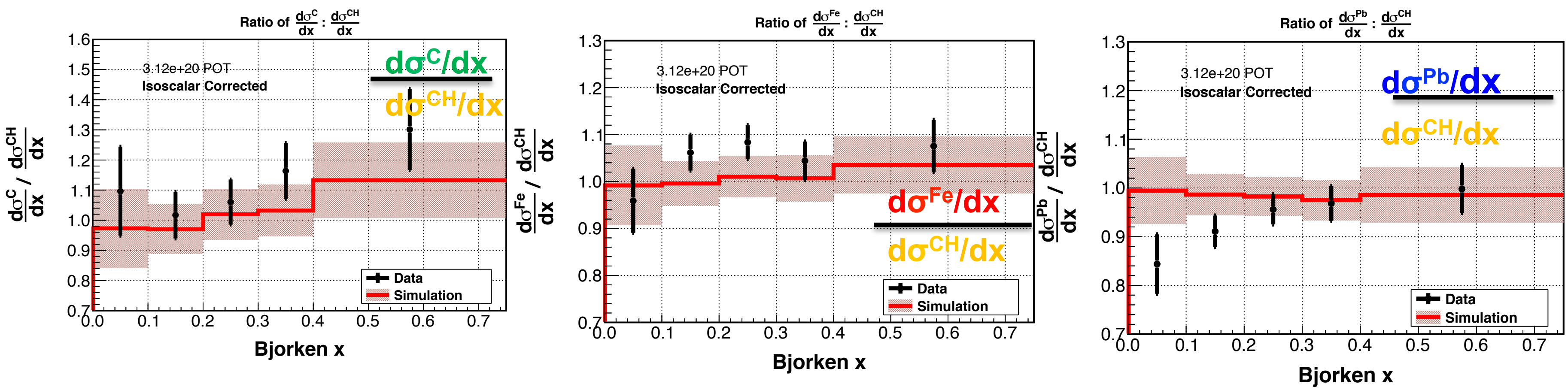
DIS cross section ratios on C, Fe, and Pb compared to CH as a function of E_ν

"Simulation" based on nuclear effects observed with electromagnetic probes

Ratios of the heavy nuclei to lighter CH are evidence of nuclear effects

Observe no neutrino energy dependent nuclear effect

DIS Cross Section Ratios – $d\sigma$ / dx_{Bj}



Unfolded x (detector smearing)

$$x_{Bj} = \frac{Q^2}{2ME_{had}}$$

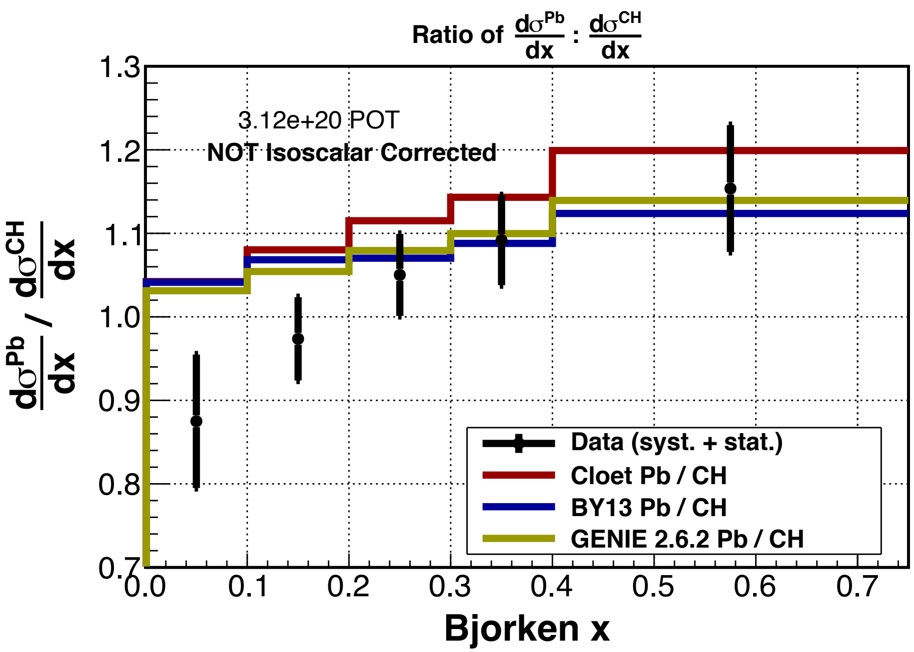
DIS: interpret data at partonic level

x dependent ratios directly translates to *x* dependent nuclear effects (cannot reach the high-*x* with LE data sample)

MINERνA data suggests additional nuclear shadowing in the lowest *x* bin ($\langle x \rangle = 0.07$, $\langle Q^2 \rangle = 2\ GeV^2$)

In EMC region ($0.3 < x < 0.7$) agreement between data and models

Shadowing in Neutrino Interactions

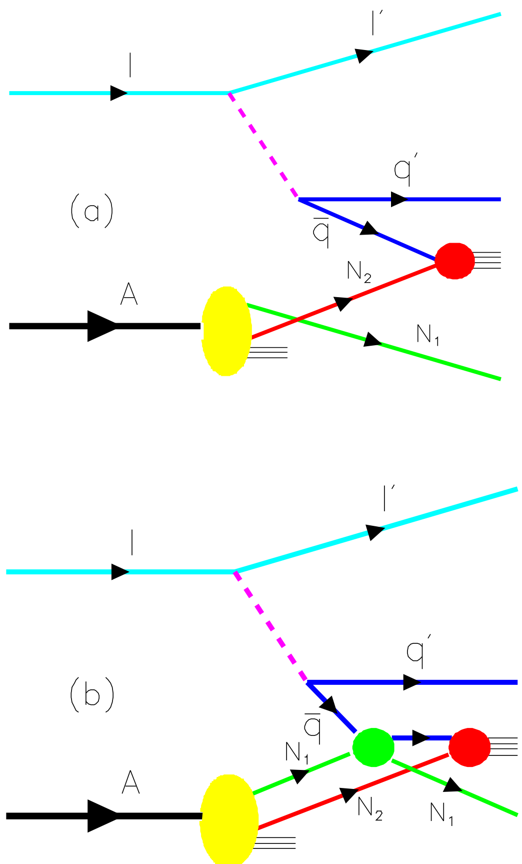


- Although not yet statistically significant the trend is certainly suggestive of something interesting happening in the low-x region of Pb/CH.
- **The data is consistent with nuclear shadowing at an <x>** (0.07) **& <Q^2 >** (2 GeV^2) **where negligible shadowing is expected with $l^{\pm}$.**

Shadowing

Nuclear Shadowing in Electro-Weak Interactions - Kopeliovich, JGM and Schmidt
arXiv:1208.6541

- Several theoretical models successfully describe the shadowing effects observed in charged-lepton nucleus scattering.
- Most are based on hadronic fluctuations of the γ (or W/Z for neutrinos)
- These fluctuations then undergo multiple diffractive scattering off leading nucleons in the the nucleus.
- The multiple scatters interfere destructively leading to no flux making it to downstream nucleons resulting in a depletion of cross section at low values of x.



Shadowing - continued

- Why low x?
- The lifetime of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters:

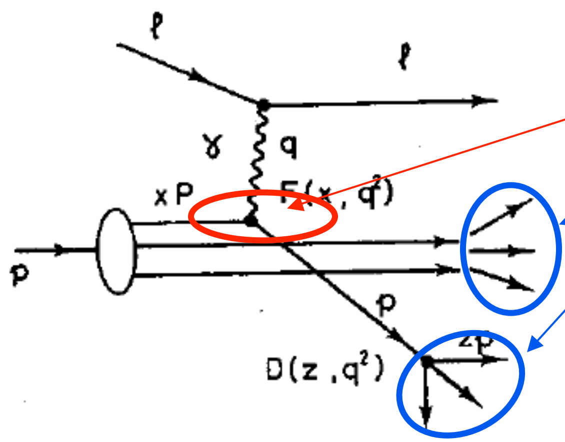
$$t_c = 2E_{had} \;/\; (Q^2 + m^2)$$

- 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 $\rightarrow$ 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

DIS Formalism

- QCD Factorization means that we can treat the scattering and later processes separately, they occur on very different timescales:

$$A(l+h \to l+X) = \sum_q \int dx A(l+q(x) \to l+X) q_h(x)$$



hard scatter: fast

fragmentation: slow

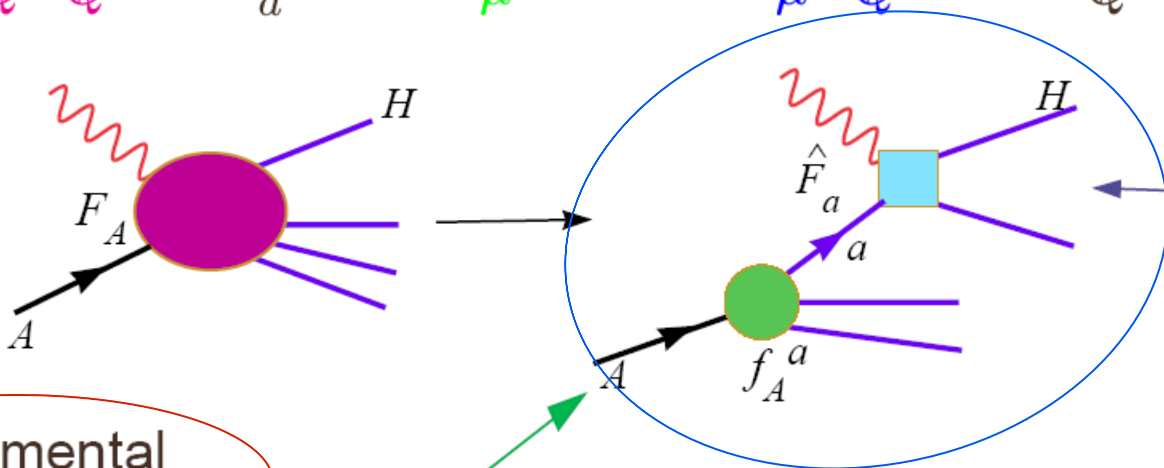
Justification for summing probabilities rather than amplitudes for ν−q scattering.

Justification for QCD factorization and other aspects of the parton model come from formal approaches, namely the operator product expansion of the hadronic tensor.

Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model – the Factorization Theorem

$$F_A^{\lambda}\left(x,\frac{m}{Q},\frac{M}{Q}\right) = \sum_a f_A^a\left(x,\frac{m}{\mu}\right) \otimes \hat{F}_a^{\lambda}\left(x,\frac{Q}{\mu},\frac{M}{Q}\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$



Experimental Input

Theoretical Calculations

Hard Cross-section
perturbative calculable
(may contain $\alpha_s^n \mathrm{Log}^n(M/Q)$)

universal Parton Dist. Fn.
Non-Perturbative Parametrization at Q_0
GLAP Evolution to Q

extracted by applying global analysis methods

<u>What do the concepts of “factorization” and “universal (nuclear) parton distributions” mean in the nuclear environment?</u>

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!**
- We may have the detector (LAr TST) (but lost the beam with nuSTORM)

Summary and Conclusions

- Nuclear effects, present in the data of all contemporary neutrino oscillation experiments, mixes topologies and changes energy between produced and (detected)final states.
- The precision with which neutrino properties can be extracted from oscillation experiments is clearly limited by the quality of the generator used.
- The neutrino generators used by experiments have grown historically into a collection of sometimes inconsistent nuclear physics recipes and still contain outdated physics modeling.
- The time has come to build a scientific community, based on NP-HEP collaboration, around the question of neutrino-nucleus interactions.
- BOTH communities will benefit from this collaboration.
- NuSTEC is in the process of becoming this NP-HEP collaboration.

Backup

In Summary: Nuclear Physics Meets Neutrino Physics

No single nuclear model comes close to fitting 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.

NuSTEC

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

GOALS:

- **Coordinate NP (theorist) - HEP experimentalist collaborative efforts:**
  - Coordinate theorist-experimentalist collaborative efforts to improve generators
  - Improve general understanding of the physics via enhanced theoretical background for experimentalists and ensuring theorists have the latest experimental data and correctly incorporated errors to test models.
- **Workshops**: Organize Community-wide Workshops when needed
  - Main Conference: The NuInt Neutrino Interaction Workshop (next, November 2015)
  - Organization beginning on workshop to investigate np-nh/MEC nuclear effects
- **Training Programs**: Organize and run training programs in:
  - Neutrino Scattering Event Generators: University of Liverpool, 14 – 16 May
  - Theory-oriented Neutrino-nucleus Scattering physics ocurred at Fermilab in October.
- **Global Fits**: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.
- **First meeting of the NuSTEC Board in September**: Representatives of each ν-A experiment, each nuclear theory “school” and each ν event generator

Green's Function Monte Carlo Techniques

Full description of initial state including N-N Correlations

- Calculations have to expand in A up to argon in the higher energy kinematical regime relevant to current/future neutrino experiments.
- Additional effort required to incorporate these models into a neutrino nucleus event generators.
- **Example of NP – HEP Collaboration to face this challenge and expand GFMC techniques to larger nuclei and increased energy E. Then to incorporate results in the GENI Event Generator**

Project Title: Nuclear Theory for Neutrino-Nucleus Interactions

R. Schiavilla and J.W. Van Orden,Old Dominion University (ODU and TJNAF)
A. Lovato), S.C. Pieper, and R.B. Wiringa (ANL)
J. Carlson and S. Gandolfi (LANL)
T.W. Donnelly (MIT)
S.J. Brice, J.G. Morfíın, G.N. Perdue, and G.P. Zeller (Fermilab)
S.A. Dytman (Pittsburgh)
H. Gallagher (Tufts)

Further Coordinated Collaboration of NP-HEP
The NuSTEC Concept

Neutrino Scattering Theorist Experimentalist Collaboration

Nuclear Physics Meets
Particle Physics

Theorists and
Experimentalists

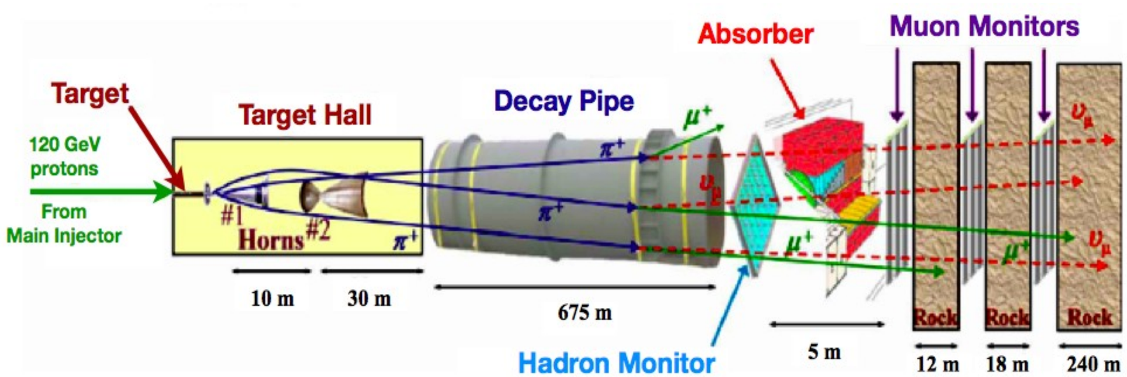
NuSTEC Training in Neutrino Nucleus Scattering Physics

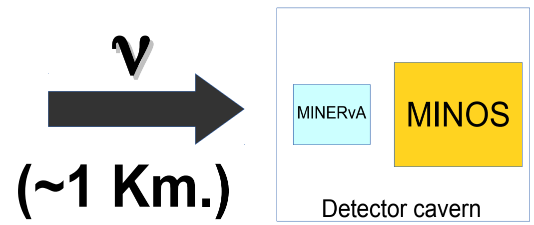
21 – 29 October 2014 with 85 International Students

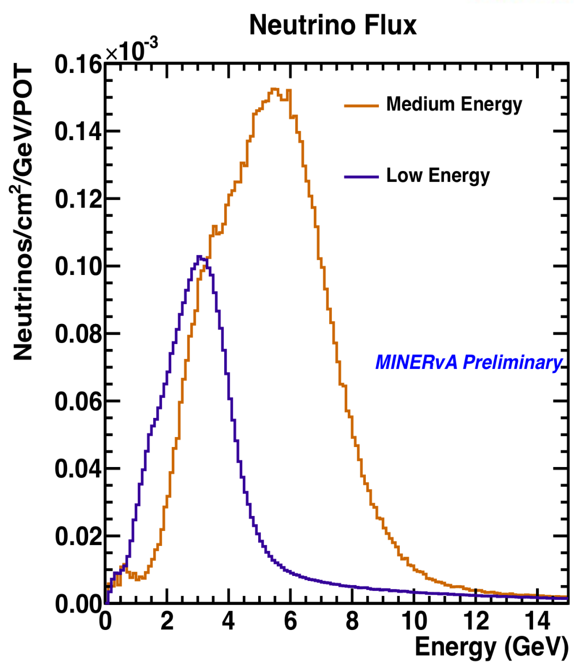
http://nustec2014.phys.vt.edu

- **Electroweak interactions on the nucleon (L. Alvarez-Ruso) [lecture videos:1,2,3]**
- **Strong and electroweak interactions in nuclei (R. Schiavilla) [lecture videos: 1, 2, 3, 4]**
- **The nuclear physics of electron and neutrino scattering in nuclei in the quasi-elastic regime and beyond (T. W. Donnelly, J. Nieves and O. Benhar)**
  - **Approximate methods for nuclei (I) (T. W. Donnelly) [lecture videos: 1,2,3]**
  - **Approximate methods for nuclei (II) (J. Nieves) [lecture videos: 1, 2, 3]**
  - **Ab initio methods for nuclei (O. Benhar) [lecture videos: 1, 2, 3]**
- **Pion production (T. Sato) [lecture videos: 1, 2, 3]**
- **Description of exclusive channels and final state interactions (P. Danielewicz) [lecture videos: 1, 2, 3]**
- **Inclusive electron and neutrino scattering in the deep inelastic regime (J. Owens) [lecture videos: 1, 2, 3]**
- **Impact of uncertainties in neutrino cross-sections (P. Coloma and T. Dealtry)**
  - General analysis (P. Coloma) [lecture videos: 1, 2]
  - The T2K analysis (T. Dealtry) [lecture video: 1]
- **Selected experimental illustrations (K. Mahn, C. Mauger and M. Soderberg)**
  - Fine-grained Sampling detector (C. Mauger) [lecture videos: 1, 2]:
  - LAr detectors (M. Soderberg) [lecture videos: 1, 2]
  - Cerenkov vs. fine-grained measurement techniques (K. Mahn) [lecture video: 1]

Brief Summary of Determining Φ(E), the Neutrino Flux: NuMI Example





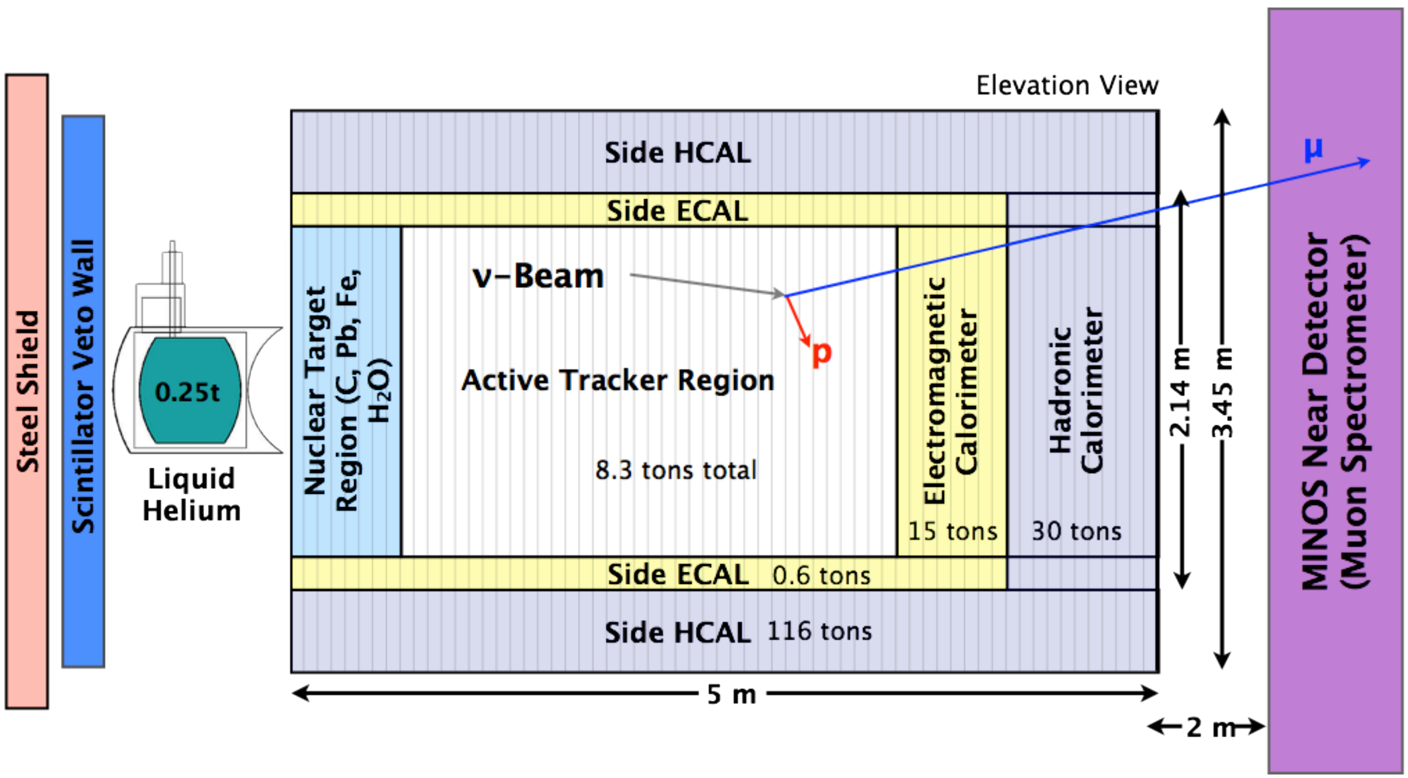


Two basic source of uncertainties:

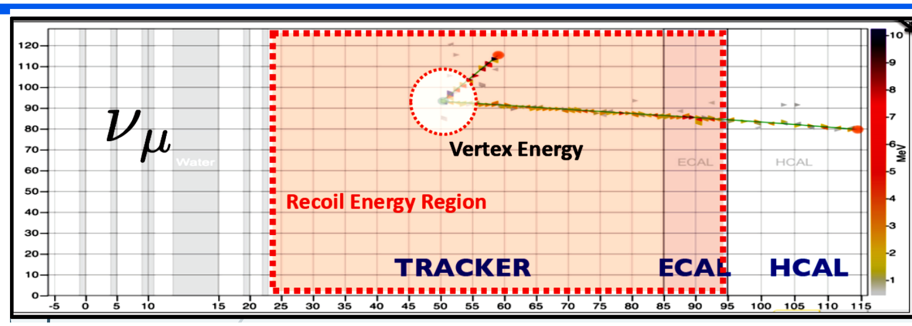
- The description of the focusing components in the Monte Carlo is uncertain or incomplete.
- The theory of the hadronic interactions is not complete (MC needs a model).

MINERνA

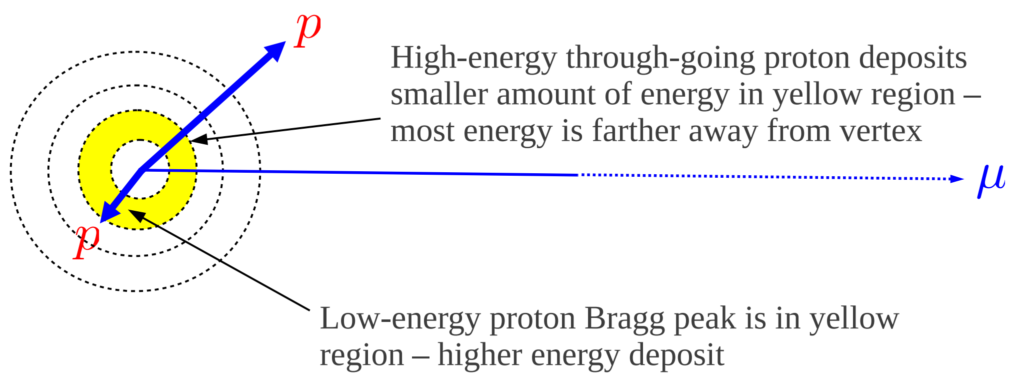
- 120 polystyrene (CH) modules for tracking and calorimetry (~32k channels)
- Tracker surrounded by electromagnetic and hadronic calorimetry.
- MINOS Near Detector provides a muon spectrometer
- Nuclear targets of C (166 Kg), Fe (653 kg) and Pb (750 Kg)



Vertex Energy



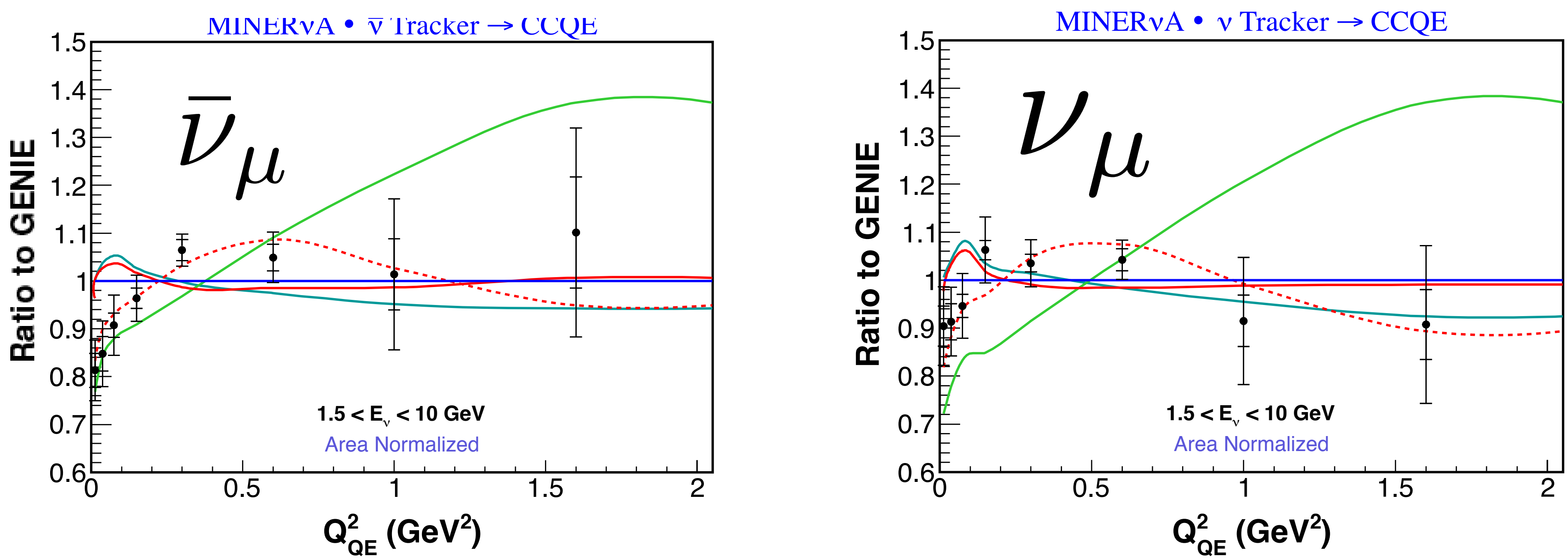
- Examine annular rings around the reconstructed vertex
  - Out to 10 cm for antineutrino (~120 MeV proton)
  - Out to 30 cm for neutrino (~225 MeV proton)



Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

MINERνA: Single Muon QE-like Analysis

Emphasis on the Shape



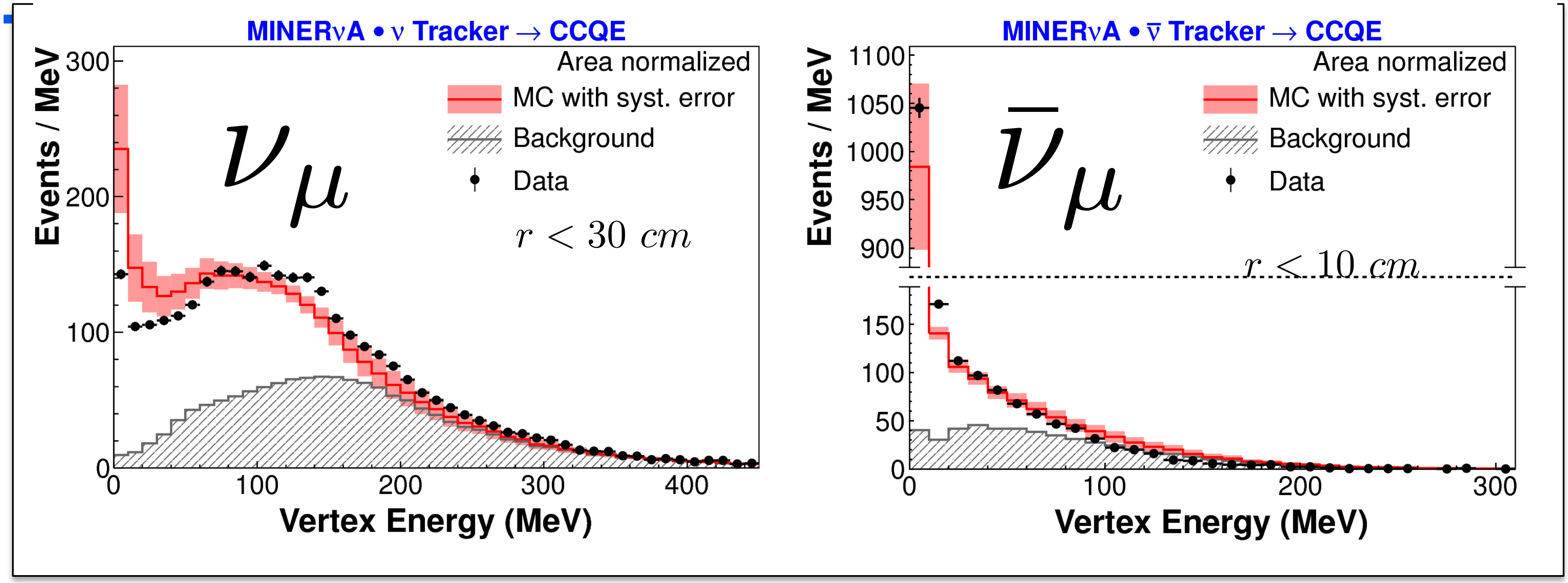
GENIE — independent nucleons in a mean field (M_A = 0.99 GeV)

M_A = 1.35 GeV — best fit to MiniBooNE data

Spectral Function — improved nucleon momentum-energy relation

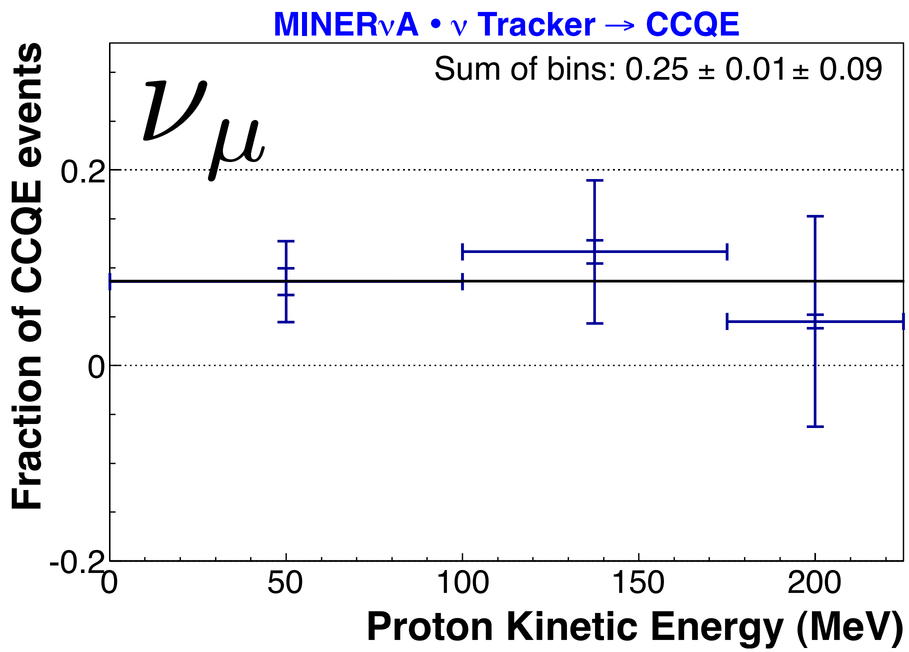
TEM (dotted) — empirical model based on electron scattering data to account for nucleon-nucleon correlations. **V current only!**

A small step to the Hadron Vertex
MINERνA Vertex Energy Analysis

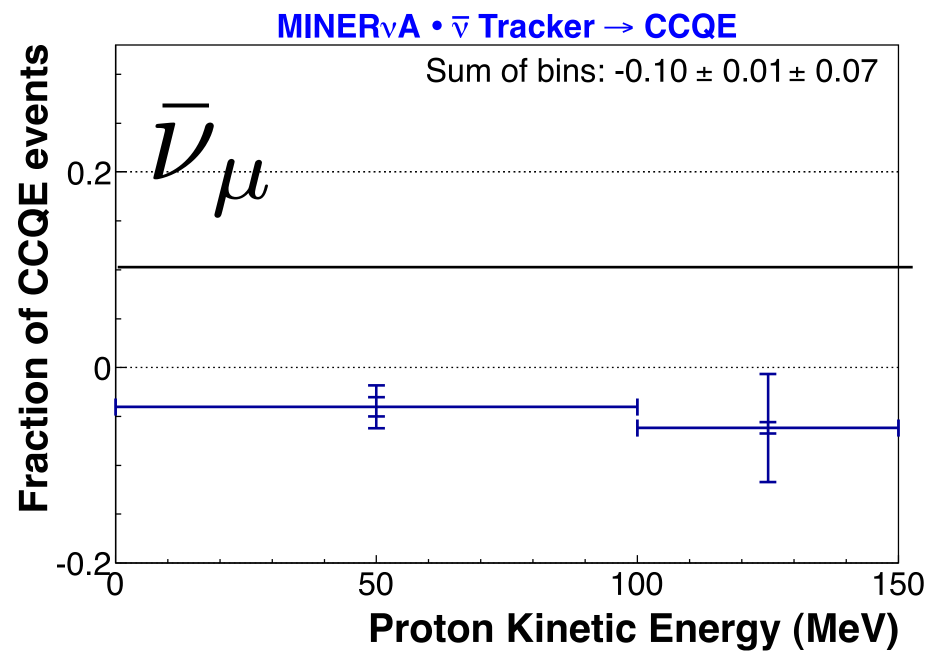


- A harder spectrum of vertex energy is observed in neutrinos.
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties.
- At this point, we make the ***working assumption*** that the additional vertex energy per event in data is ***due to protons***

Vertex Energy – suggestion of additional protons coming out of the nucleus in neutrino interactions



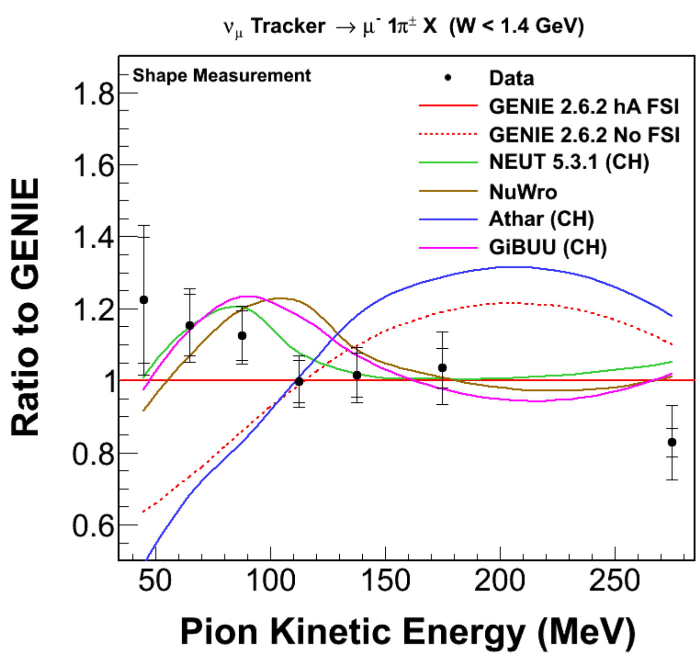
The fit wants to add an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events to** improve agreements with data

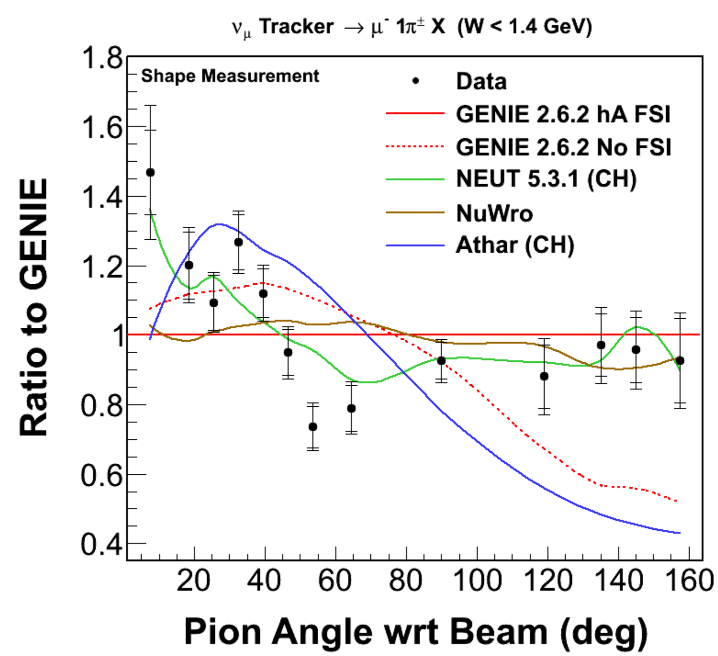


No such additional proton is required for antineutrinos. Slight reduction if anything. **(-10 ± 7)% of QE events**

More details: charged pion (W<1.4 GeV) model shape comparisons

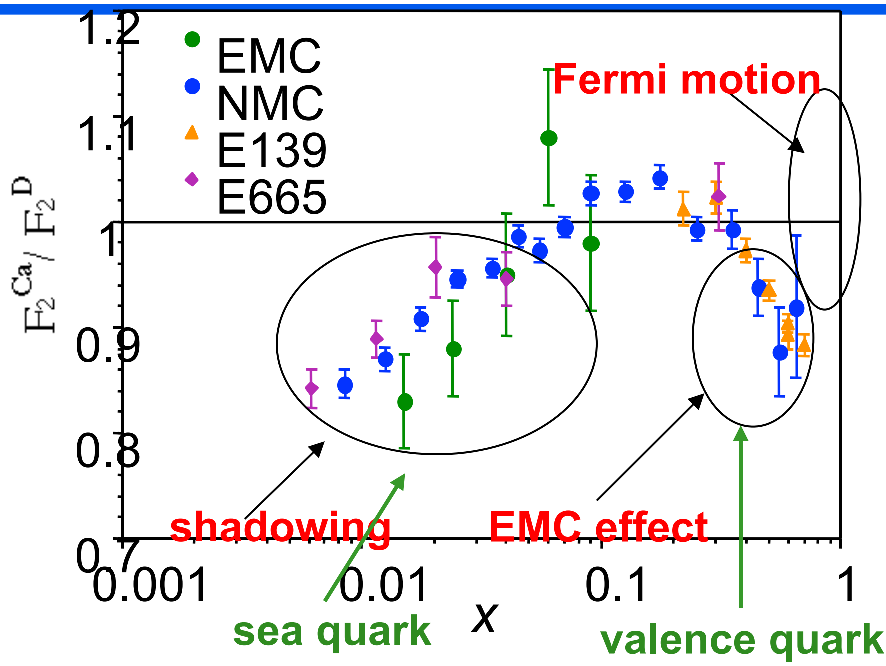
- Each calculation is normalized to data, show ratio to GENIE w/FSI

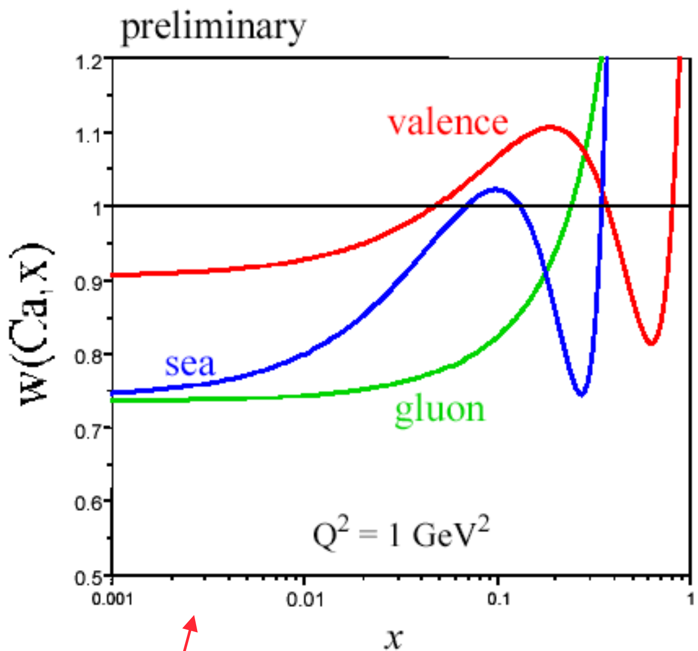




- GiBUU, NuWro, NEUT and GENIE all predict the data shape well
- Data sensitive to the details in pion interaction models
- Athar does not agree with data. Likely due to insufficient FSI.

Studies of DIS x-dependent Nuclear Effects with Neutrinos

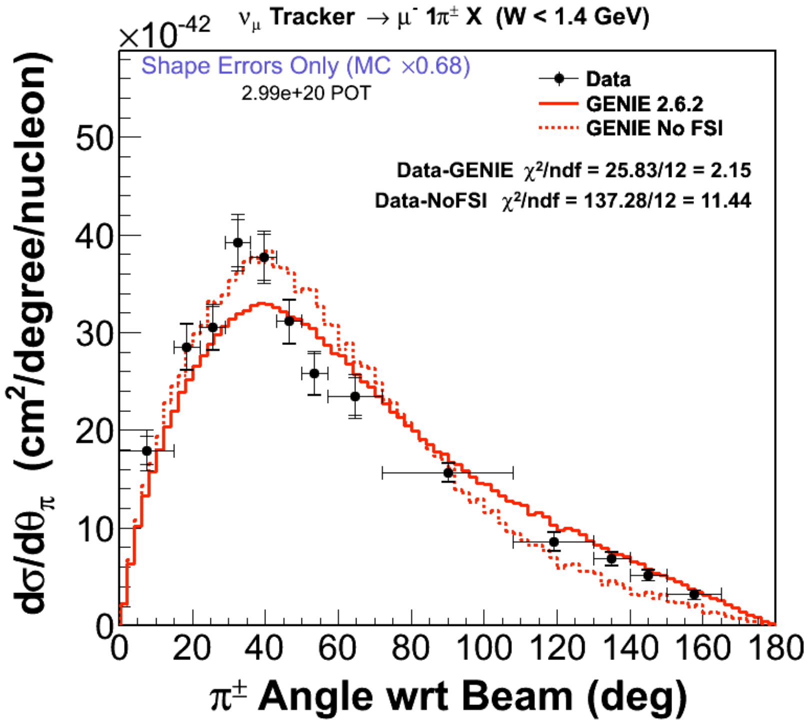


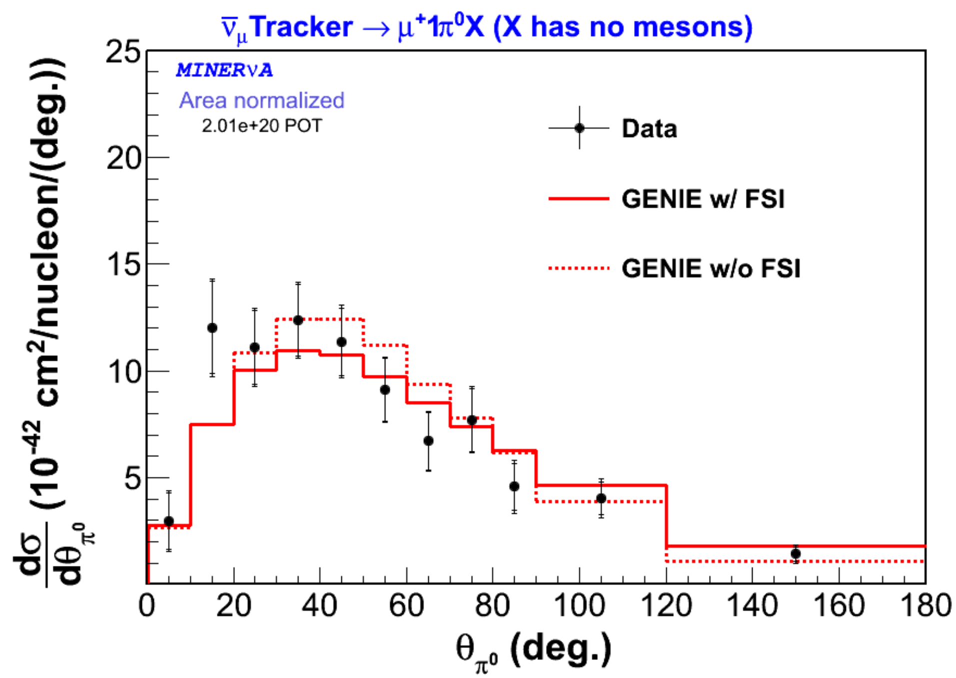


- F_2 / nucleon changes as a function of A. Specifically measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **SPECULATION: Stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

FSI Conclusions for Pion Angle

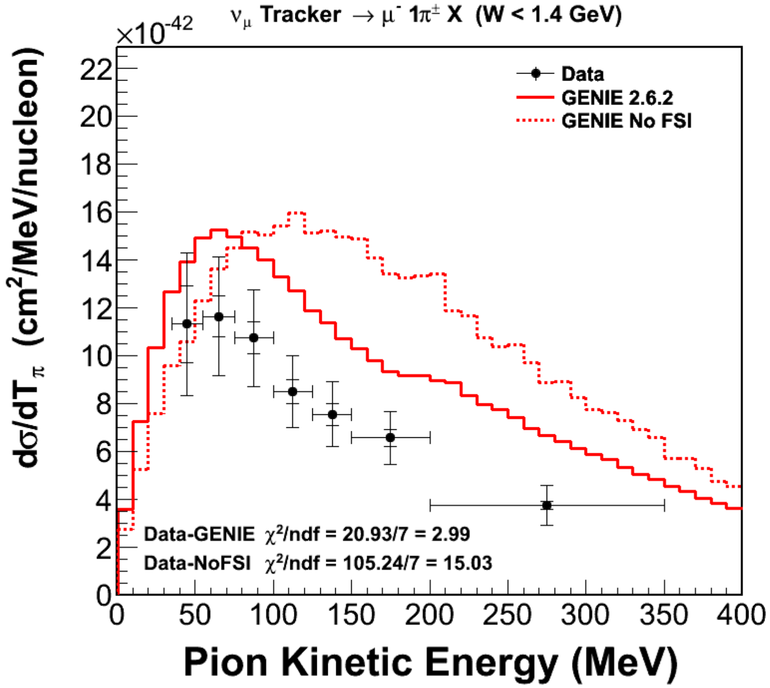
(Shape Comparisons)

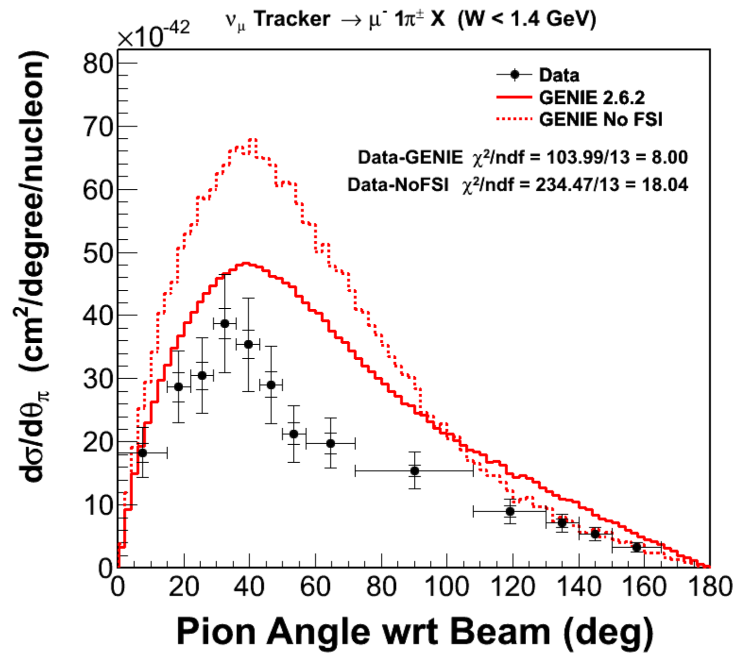




- Data prefer GENIE with FSI

More details: charged pion (W<1.4 GeV) absolute cross sections





- GENIE (MC) magnitude is too large with only a small dip
- Model with FSI strongly favored over no FSI

Suggested Improvement: full description of initial state including N-N Correlations

Green's Function Monte Carlo Techniques

ANL - A. Lovato, S. C. Pieper, and R. B. Wiringa

- Current neutrino event generators:
  - Generally lag behind theory by decades and are an assembly of multiple independent processes that require additional care to be combined.
  - Eg. beware double counting when combining spectral functions with MEC.
- Quantum Monte Carlo (QMC), in particular Green's Function Monte Carlo (GFMC), methods make it possible to carry out first-principle, exact calculations of nuclear properties for light nuclei (to carbon) .
- GFMC
  - based on realistic Hamiltonians including two- and three-nucleon potentials.
  - Calculations retain the full complexity of the many-body correlations
  - reproduce very well the observed energy spectra of A = 2 – 4 nuclei, and the ground-state and low-lying excited-state energies of nuclei in the mass range A = 6 – 12.
- GFMC still need to incorporate crucial dynamical aspects into theoretical models to provide a reliable description of the interactions between a neutrino and a heavy nucleus
  - correlations, many-body currents, and interference effects.

Quasi-elastic (QE) Neutrino Scattering

Here from a free nucleon

first derived by C.H. Llewellyn-Smith

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[\boxed{A(Q^2)} \mp \boxed{B(Q^2)}\frac{(s-u)}{M^2} + \boxed{C(Q^2)}\frac{(s-u)^2}{M^4}\right]$$

The vector form factors (F_V^1 and F_V^2) can be related to the nucleon electromagnetic form factors, which are described by electron scattering data.

A first order approximation (Goldberger-Treiman relation) relates the pseudoscalar form factor (F_P) to the axial form factor.

The axial form factor (F_A) is approximated by the dipole form.

nuclear β-decay experiments

$$F_A(Q^2) = \frac{F_A(Q^2{=}0)}{\left(1 + {Q^2}/{M_A^2}\right)^2}$$

Axial Mass

Extracted from neutrino quasi-elastic cross-section measurements.