Status and Challenges of Neutrino Nucleus Interaction Physics

A road to further NP- HEP ν Physics Collaboration

Jefferson Lab Seminar
21 September 2018

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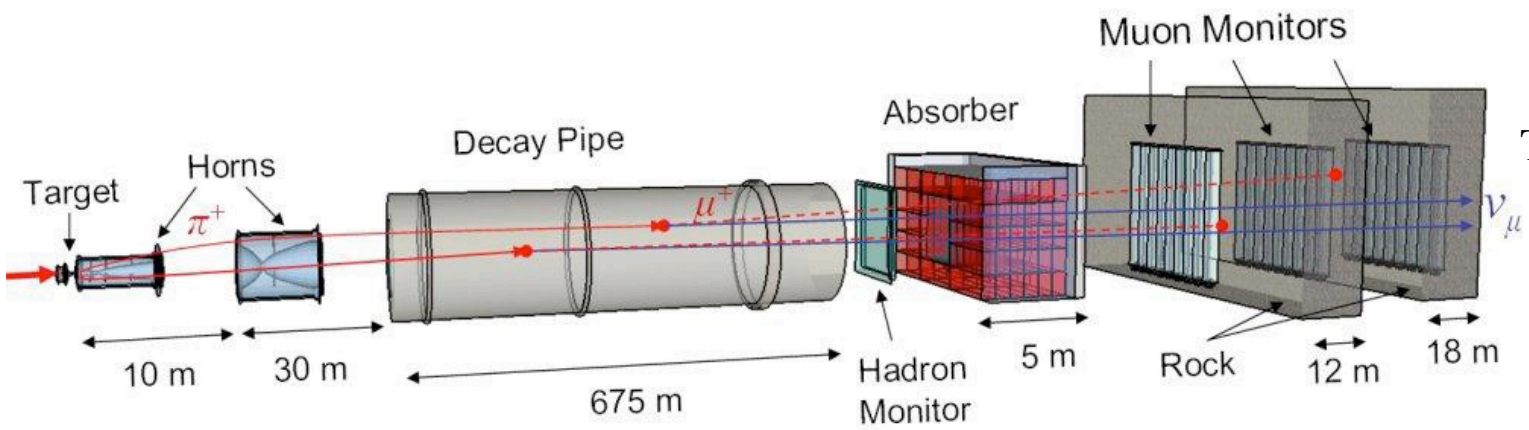
Fermilab

The Tantalizing Goal of the US Neutrino Community

and the **Hazards** that Block the Way

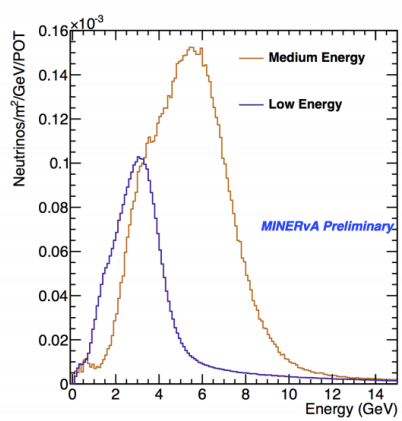
A quick reminder of the overriding sources of the challenges?

A Typical Accelerator Neutrino (NUMI) Beam

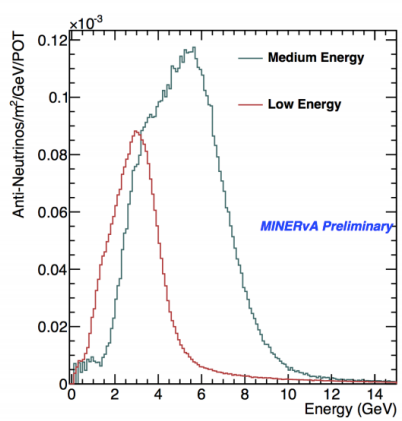


Towards Detector

Neutrino

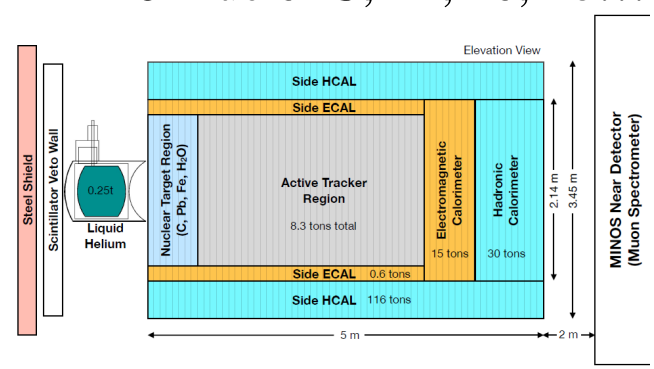


Anti-neutrino



Neutrinos with wide range of possible energy

Detector composed of nuclei C, Ar, Fe, Pb…



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

What we observe in our detectors constructed of heavy nuclei.

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

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

⊗

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

⊗

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

⊗

~~Detector Properties and Effects~~

Neglect in the following

Neutrino Nucleus Scattering

What we observe in our detectors

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

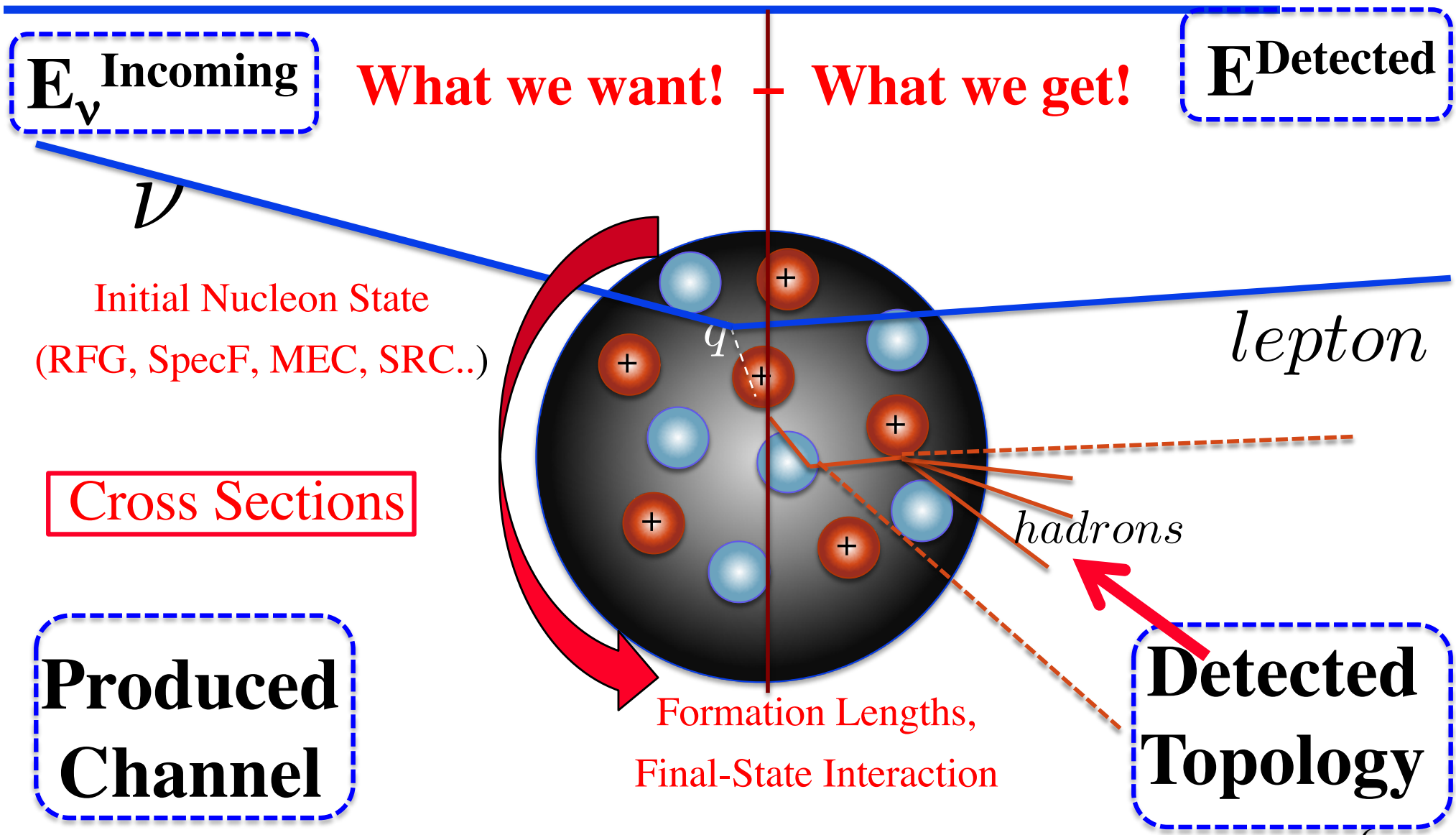
$$\mathbf{Y_{c\text{-}like}(E_d)} \;\; \alpha \;\; \phi_\nu(E \geq E_d) \;\; \otimes \;\; \sigma_{c,d,e..}(E \geq E_d) \;\; \otimes \;\; Nuc_{c,d,e..\rightarrow c}(E \geq E_d)$$

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

- The energy E_d 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>**

Nuclear Physics of GeV ν-nucleus Interactions



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⊗

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⊗

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

(Both initial and final state effects)

We call cross terms within the ▭ the **"Nuclear Model"**

Neutrino Nucleus Scattering

What we observe in our detectors

Neutrino Flux Term

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

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

- ϕ_ν **(E)** is the energy dependent neutrino flux that enters the detector.
- We can, with considerable effort, estimate the incoming energy distribution with sophisticated Monte Carlos that depend on knowledge of the hadron production spectra off the target. With careful modeling of the beam components it is no better than ≈ 8-9 % absolute and energy-bin to energy-bin accuracy
- Recent results from the MINERvA Collaboration suggest that measurements of the theoretically well known $\boldsymbol{\nu_\mu + e \rightarrow \nu_\mu + e}$ process can be used to constrain the flux to absolute (6-7)% level.

Neutrino Nucleus Scattering

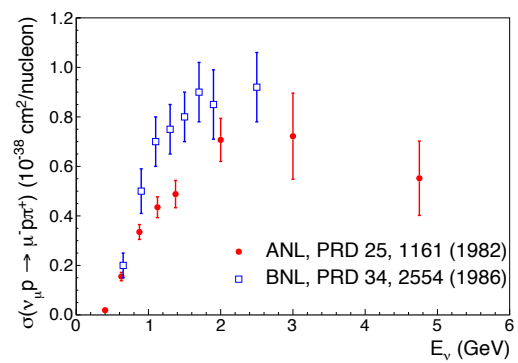
Cross Section Term: $\sigma_{c,d,e..}(E \geq E_d)$

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

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

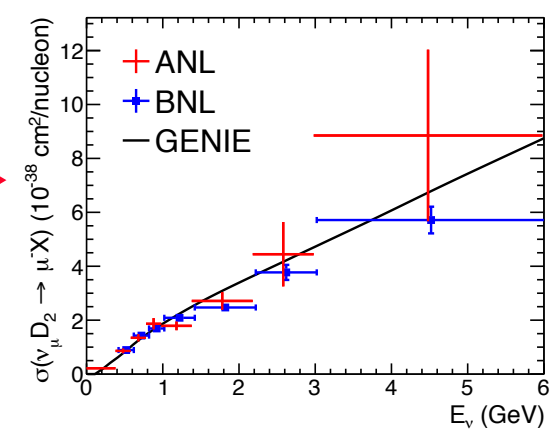
- $\sigma_{c,d,e..}(E_d)$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus.**

- **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 we are still limited by the statistical and systematic errors of this old data input to our model!**

There is a real NEED for a Modern High-statistics ν-Nucleon Scattering Experiment – NP Community Welcome to Join!

3-day workshop on just this topic at INT in Seattle in June – INT 18-2a

Details of the need for any given neutrino interaction channel can be found in:

NuSTEC White Paper: Status and Challenges of Neutrino–nucleus Scattering:

Progress in Particle and Nuclear Physics 100 (2018) 1–68

- General challenges facing the community:
  - Future high-precision neutrino interaction experiments are needed to extend the current program of GeV-scale neutrino interactions and should include a **high statistics hydrogen or deuterium scattering experiment to supplement the currently poorly known (anti)neutrino–nucleon cross sections**.

- Quasi-elastic Scattering:
  - **improvement of our knowledge of the axial part of the nucleon–nucleon transition matrix elements and will help to factorize nucleon cross-sections and nuclear uncertainties such as Fermi momentum or final state interactions.**

The Need for a Modern High-statistics ν-Nucleon Scattering Experiment – NP Community Welcome to Join!

- Resonance Production:
  - The most important challenges are **improving knowledge of the axial part of nucleon-Δ transition matrix elements, either via a new hydrogen and/or deuterium experiment** or via lattice-QCD calculations;

- SIS and DIS Scattering (W > 1.4 GeV):
  - Multiplicities - a statistically significant measurement of multiplicities off of H/D target would certainly improve ν-nucleon hadronization models (fragmentation functions) and enable more accurate assessments of models of final state interactions

- **The workshop concluded with clear support from the participants of the nuclear, astro-particle and high-energy communities that such a new high-statistics H/D experiment would be extremely helpful. There is a very possible way to stage such an experiment using a DUNE near detector.**

Neutrino Nucleus Scattering

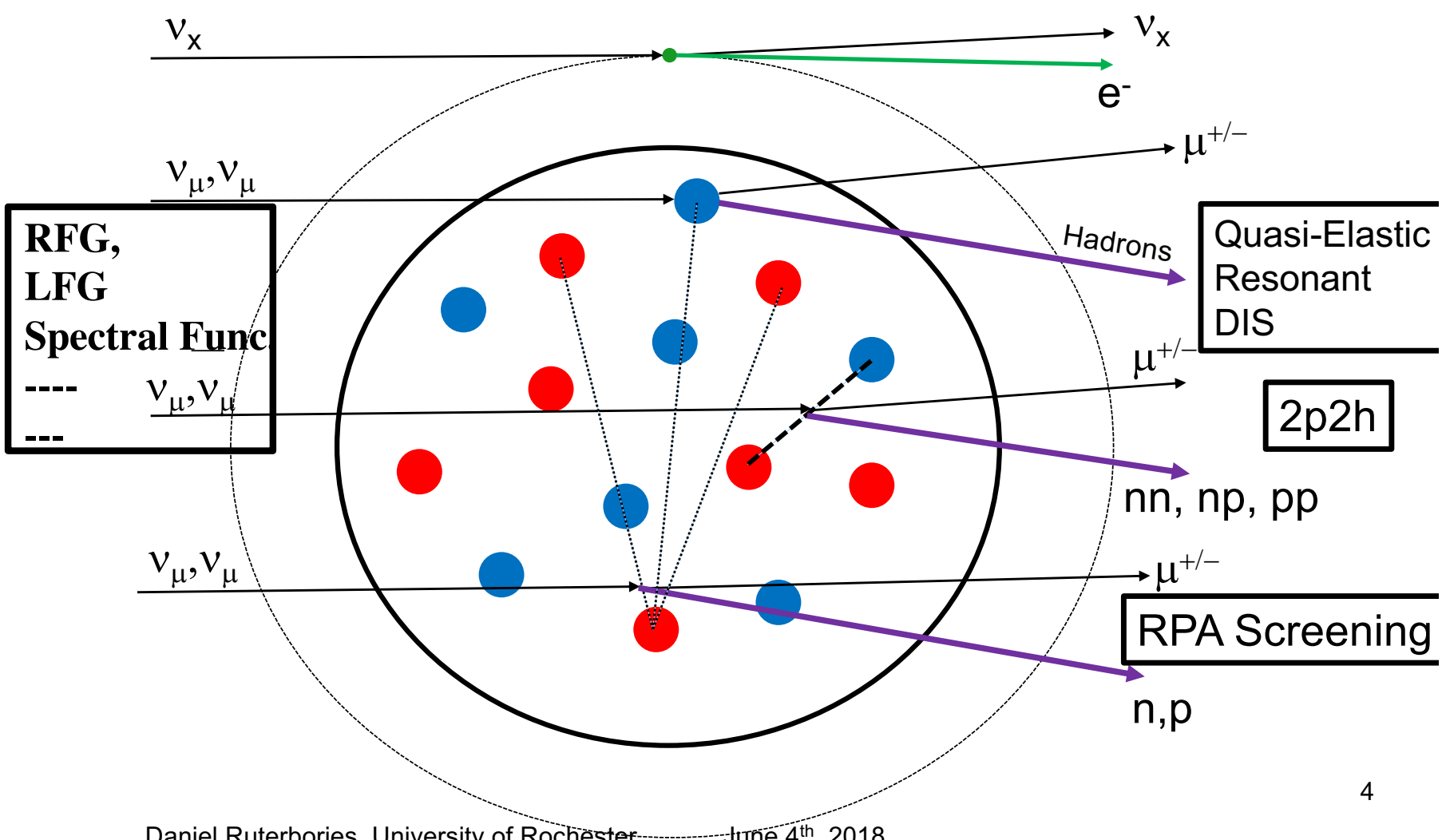
Nuclear Effects Term: $Nuc_{c,d,e..\rightarrow c}(E \geq E_d)$

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

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

- **$Nuc_{c,d,e..\rightarrow c}(E \geq E_d)$ – 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 produced 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?**

The Big Picture of the Initial State Interaction



The Big Picture of Final State Interactions (FSI)

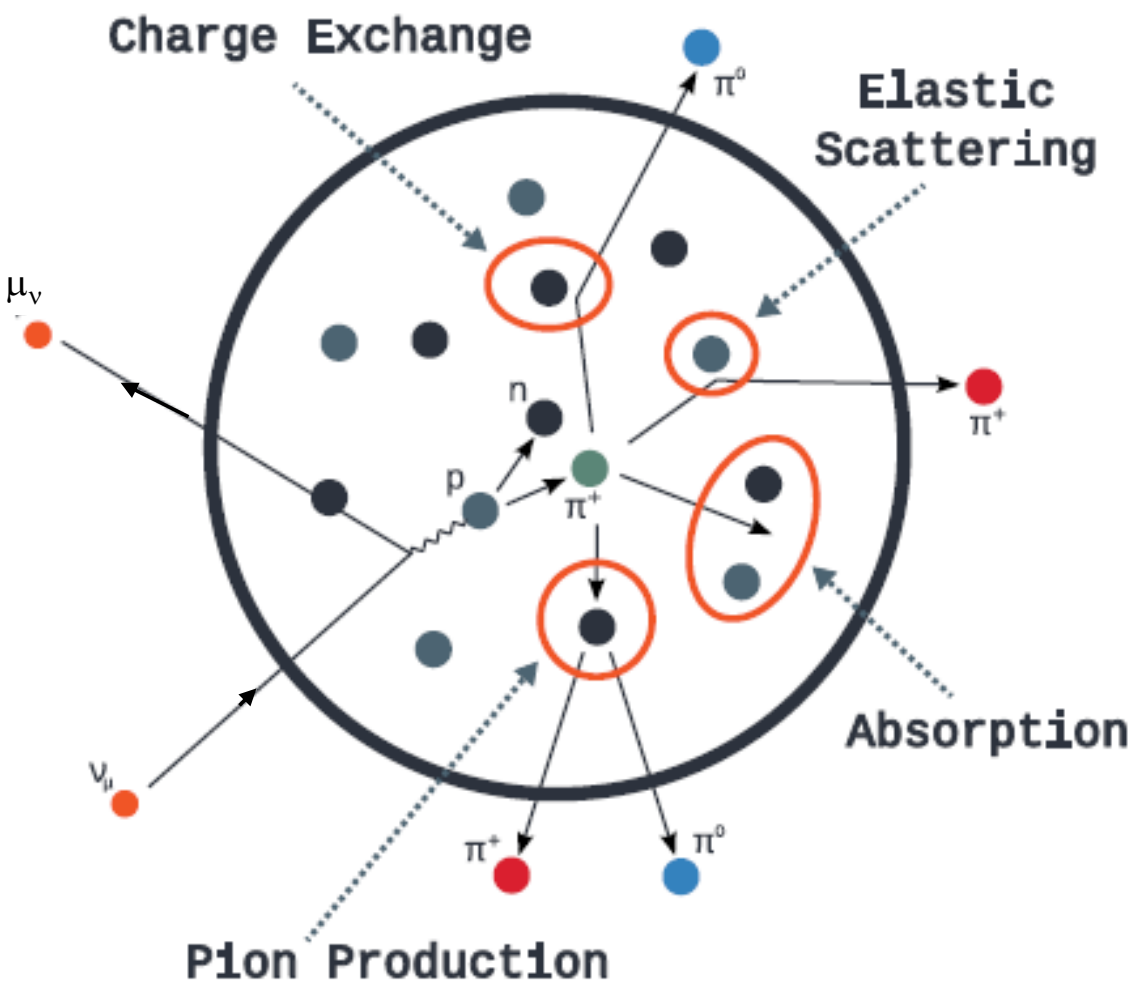


Figure by Tomasz Golan

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 <u>even with a near detector!</u>

<u>How do we constrain/improve the nuclear model?</u>

Four Main Neutrino Event Simulators – Different Nuclear Models in Each

How do we constrain/improve the nuclear model?

The GENIE Neutrino Monte Carlo Generator C. Andreopoulos (Rutherford) *et al.*. May 2009. 34 pp.
Published in **Nucl.Instrum.Meth. A614 (2010) 87-104**
FERMILAB-PUB-09-418-CD
DOI: 10.1016/j.nima.2009.12.009

e-Print: **arXiv:0905.2517 [hep-ph] | PDF**

GENIE

A neutrino interaction simulation program library NEUT Yoshinari Hayato (Kamioka Observ.). 2009. 13 pp.
Published in **Acta Phys.Polon. B40 (2009) 2477-2489**

NEUT

NuWro Monte Carlo generator of neutrino interactions - first electron scattering results
Jakub □muda, Krzysztof M. Graczyk, Cezary Juszczak, Jan T. Sobczyk (Wroclaw U.). Oct 12, 2015. 6 pp.
Published in **Acta Phys.Polon. B46 (2015) no.11, 2329**
DOI: 10.5506/APhysPolB.46.2329

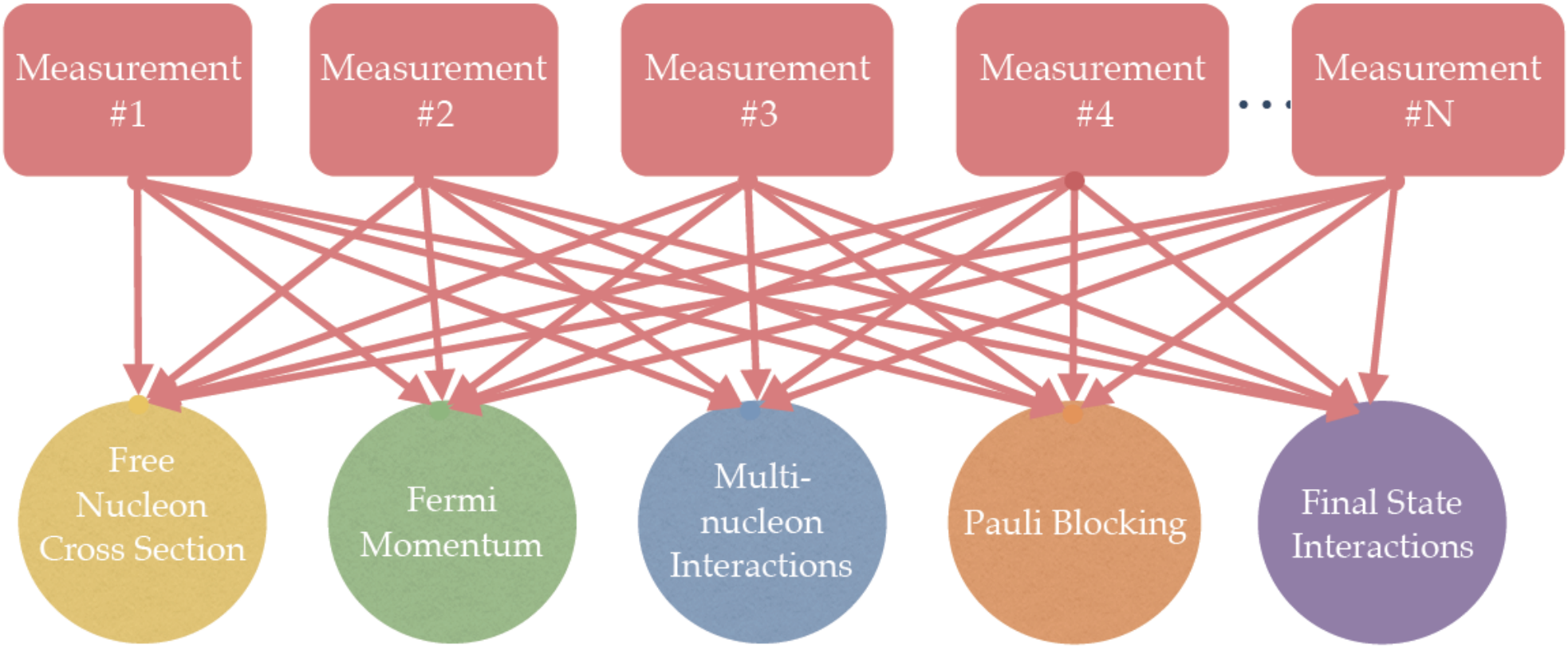
e-Print: **arXiv:1510.03268 [hep-ph] | PDF**

NuWRO

Neutrino nucleus reactions at high energies within the GiBUU model O. . Lalakulich, K. Gallmeister, T. Leitner, U. Mosel (Giessen U.). Jul 2011. 7 pp.
Published in **AIP Conf.Proc. 1405 (2011) 166-172**
DOI: 10.1063/1.3661579
e-Print: **arXiv:1107.5944 [nucl-th] | PDF**

GiBUU

MINERvA Approach to Constraining the Nuclear Model



L.Fields

Where are we now?

Brief survey of success and not so much..

- **Quasi-elastic: Major focus of study of MINERvA, T2K and NOvA experiments**.
  - All mainly on C (A-dependent measurements from MINERvA),
  - all with relatively (for ν-A experiments) minimal statistical errors and (6-10)% flux errors, (10-20)% nuclear model errors and ≈ 5% detector uncertainties.

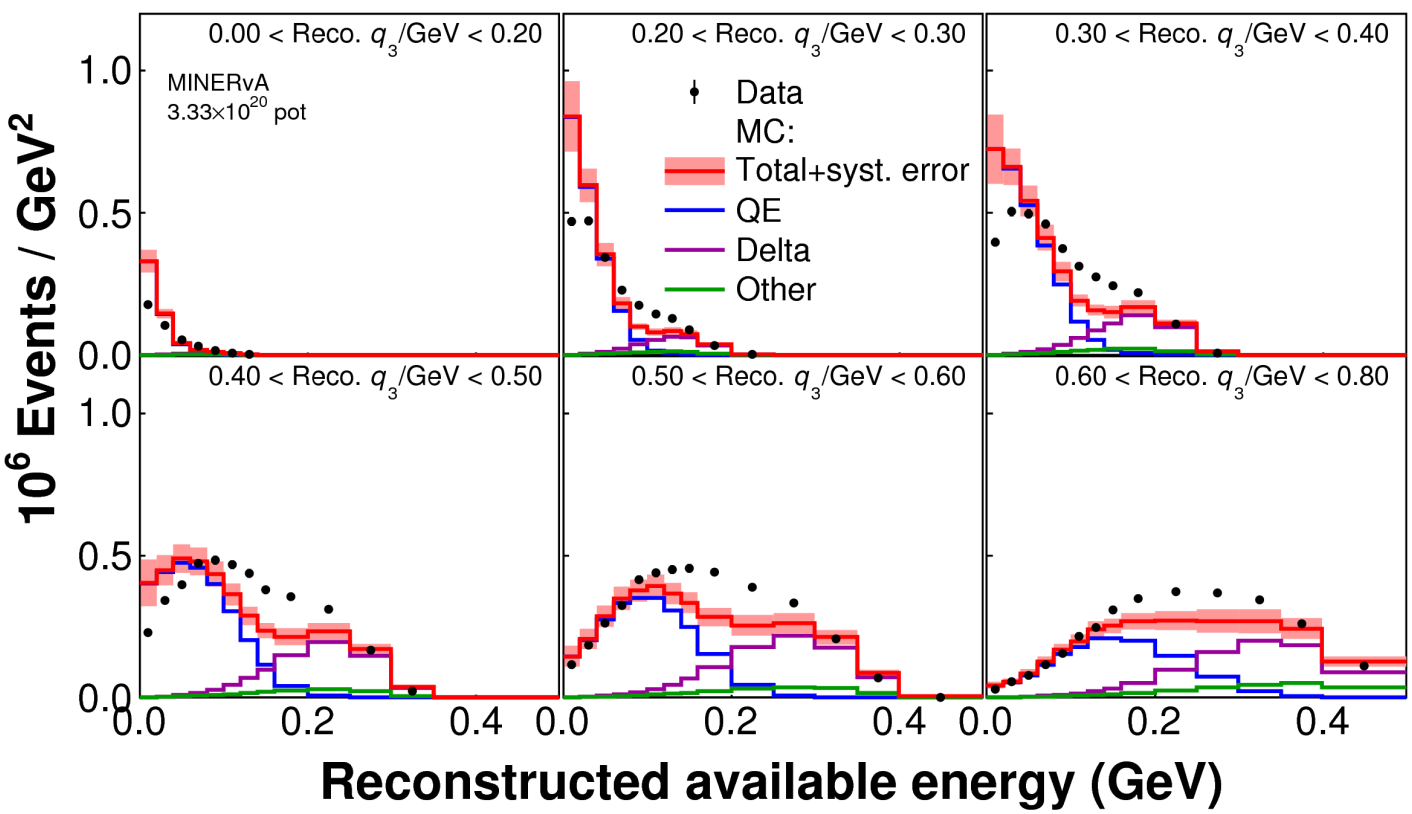
- Delta Production: Major focus of MINERvA and more minimal contributions from NOvA and T2K due to neutrino energy range. Statistical errors larger than QE, much larger GENIE uncertainties and roughly similar detector uncertainties except for π^0 studies that have larger systematics.

- **Above the Delta an increasingly dark and dangerous place full of unknowns. Perhaps the thing we know best there is the flux!**

Very successful example of where are we now.

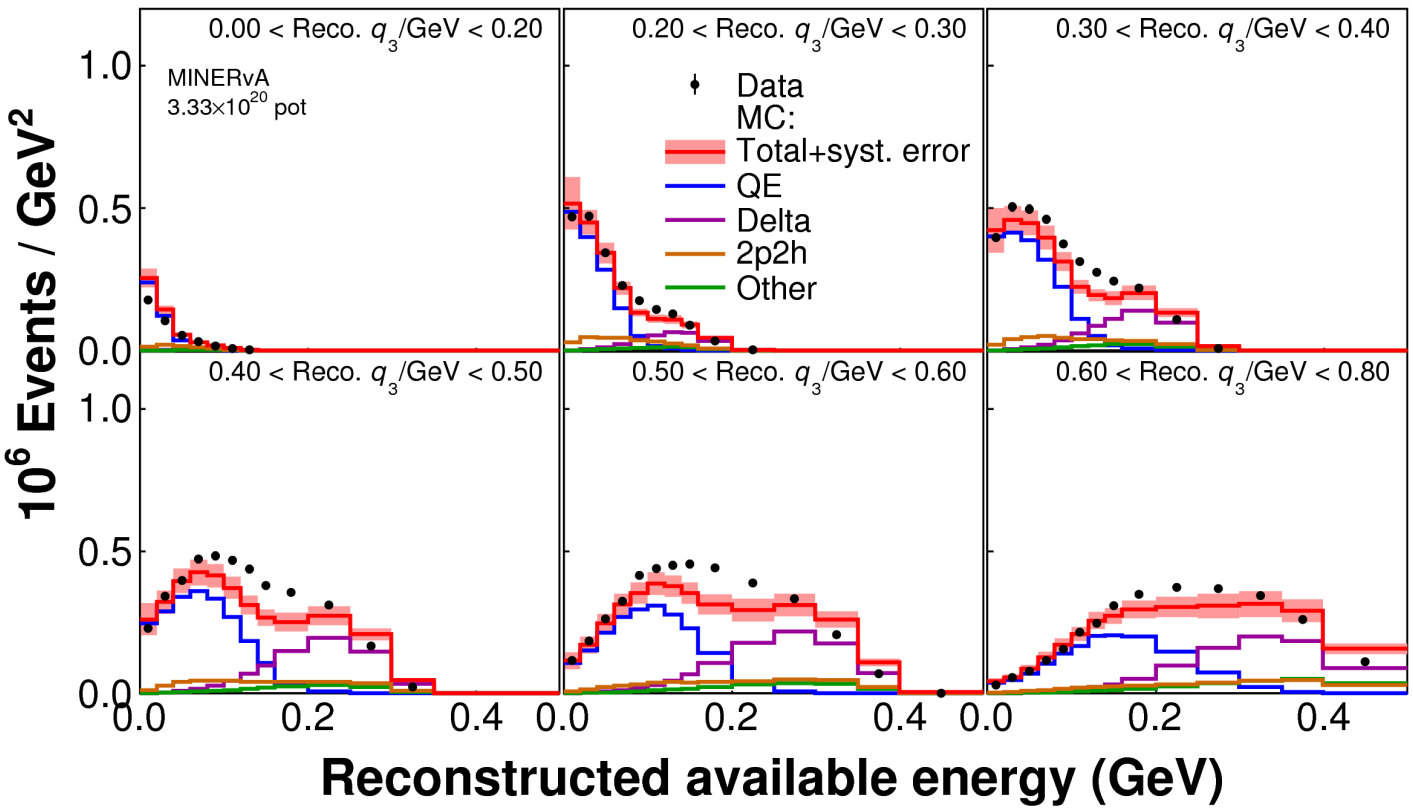
Use recent MINERvA Study of QE and Between QE and Δ

- Use current GENIE models for QE and Delta production:
- Observed events versus GENIE prediction as a function of energy in q_3 bins (momentum of q vector):



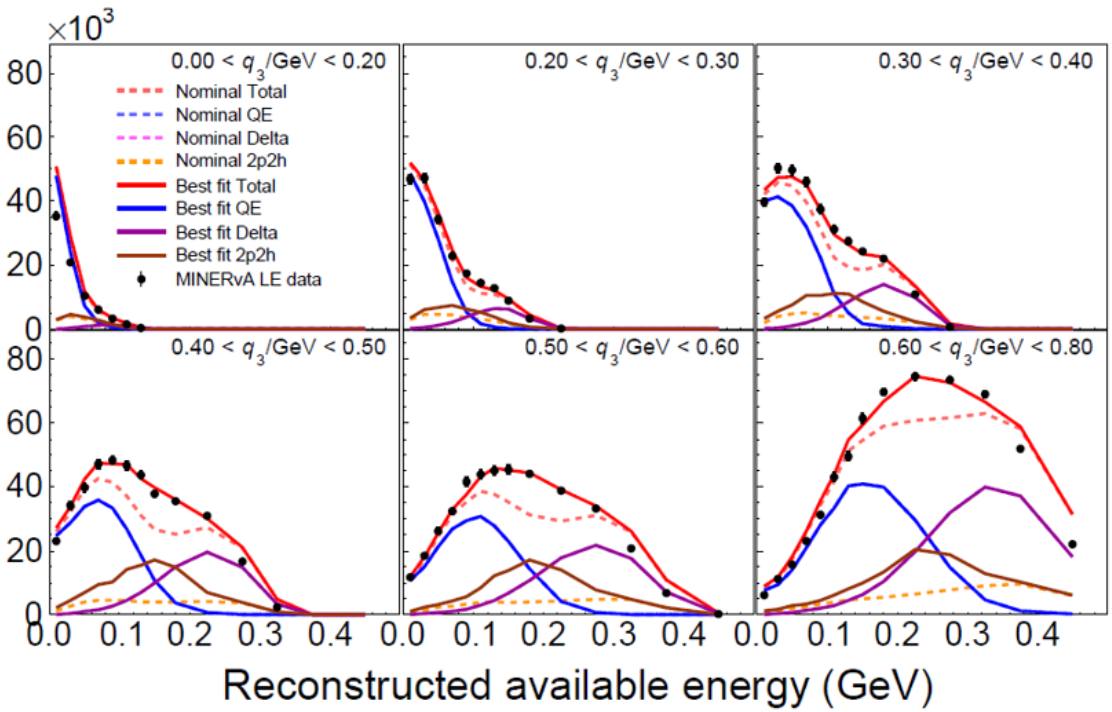
Introduce Valencia Model RPA and 2p2h

- Let's now add RPA and correlated nucleon pair corrections (2p2h) using the Valencia Model.
- It shrinks the difference but is not enough….



Form what we call the "Minerva tune (MnvGENIE)" composed of RPA+2p2h+Low recoil fit+(non-resonant pion reduction)

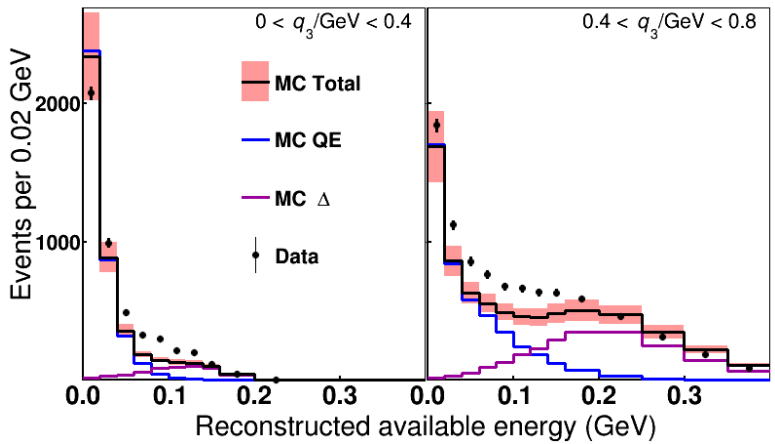
- Fit a 2D Gaussian in true (q_0,q_3) as a reweighting function to the 2p2h contributions to get the best agreement
- **Only reweight 2p2h although the missing strength could be coming from QE and/or Delta and/or 2p2h!!**
- No assurance that this fit works for other nuclei or energies. Possible fit with other neutrino energy spectra on C in the works….



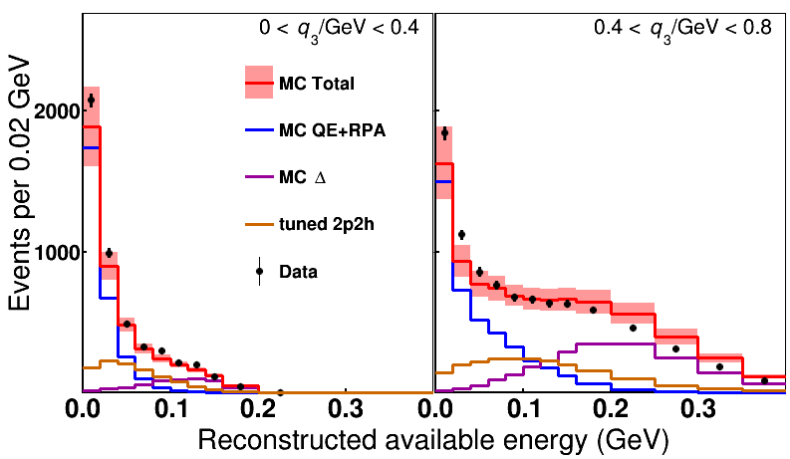
Does it work for other samples? Yes, major accomplishment

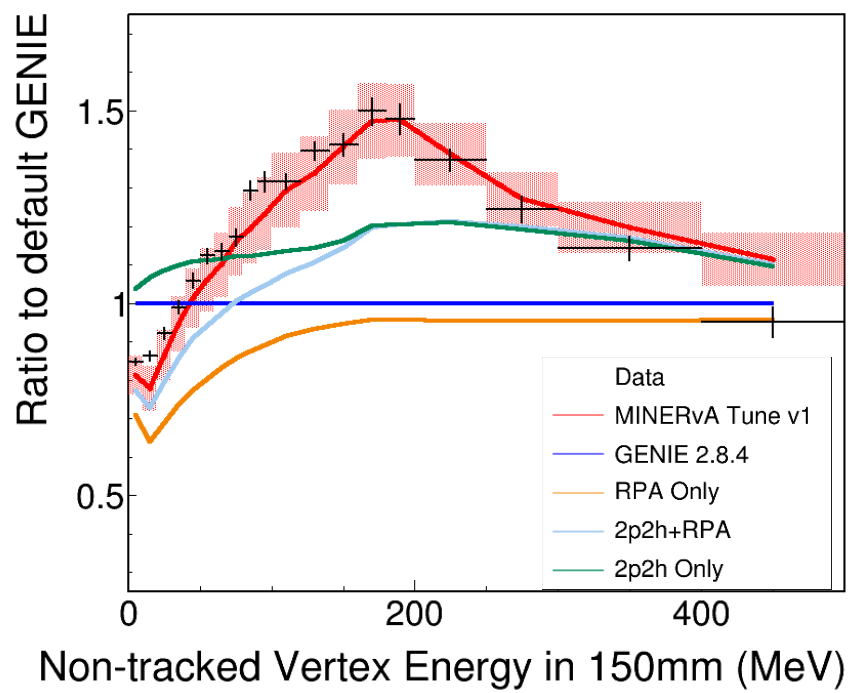
- This reweight works, **surprisingly**, for antineutrino **(WHY?)** and vertex energy as well

$\bar{\nu}$ **before** enhancement with MINERvA tune



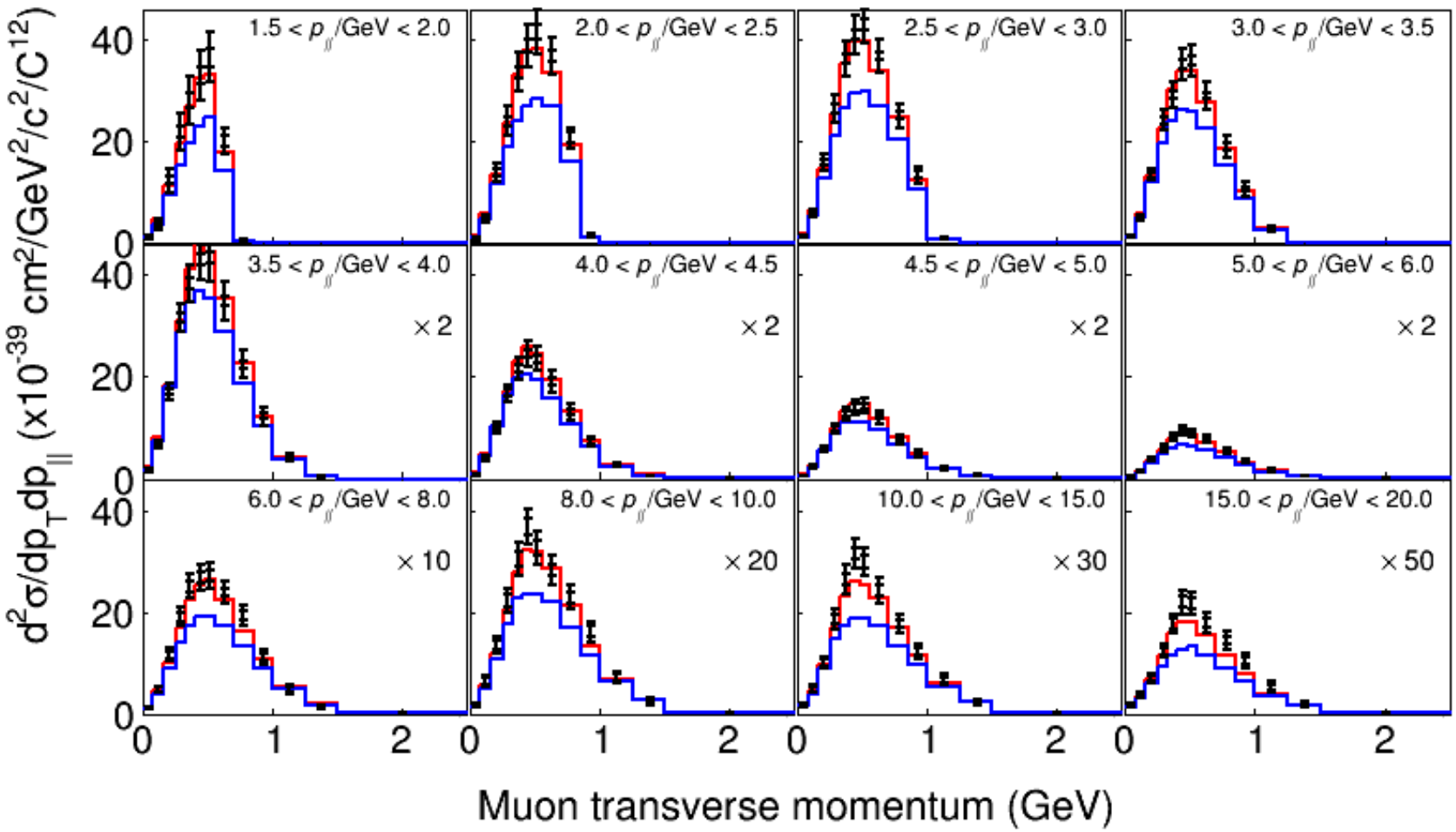
$\bar{\nu}$ **after** enhancement with MINERvA tune





Does it work for other more exclusive samples? Yes, major accomplishment – (Why does it work so well?)

Neutrino CCQE-like



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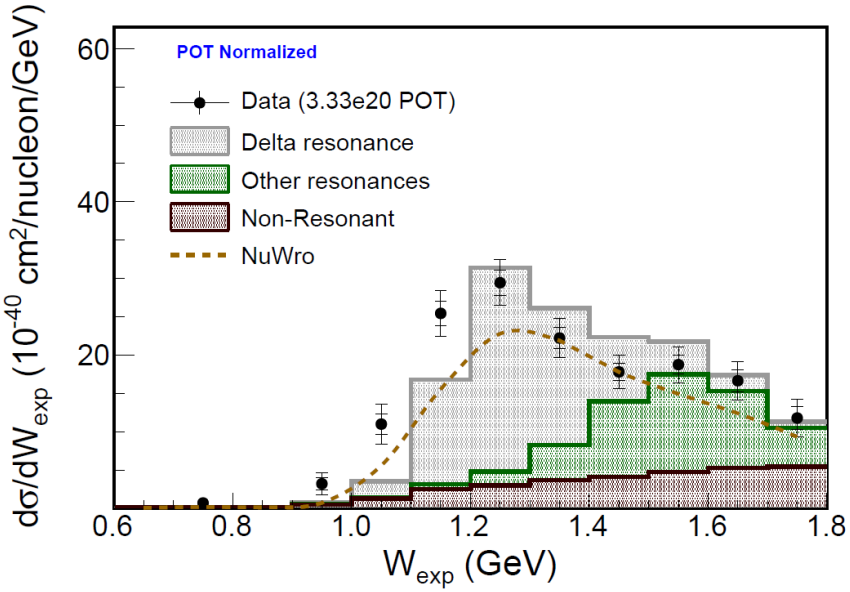
What's going on here?

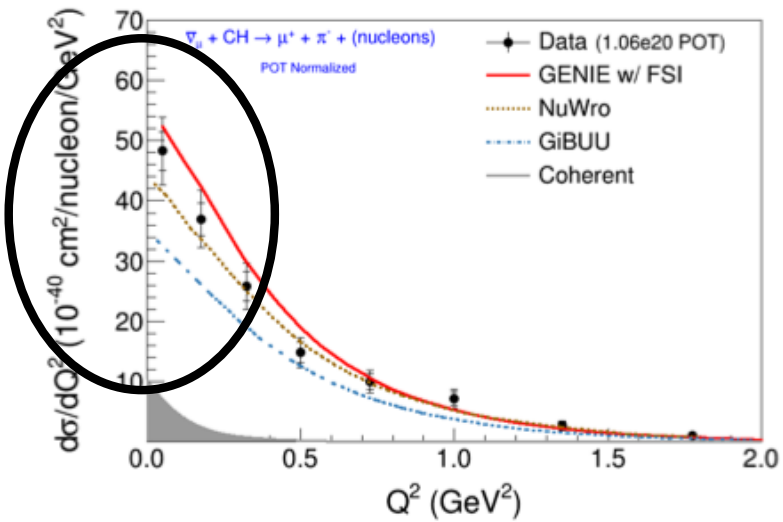


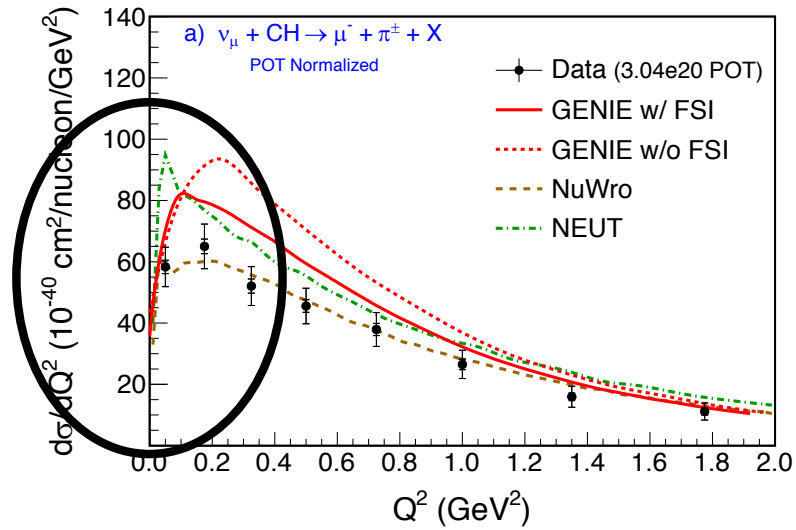
- W_{exp} is derived assuming kinematics of a struck nucleon at rest
  - Neither GENIE nor NuWro take into account interference between resonant and non-resonant processes
  - Fermi-motion simulation
  - In medium modification of Δ(1232)

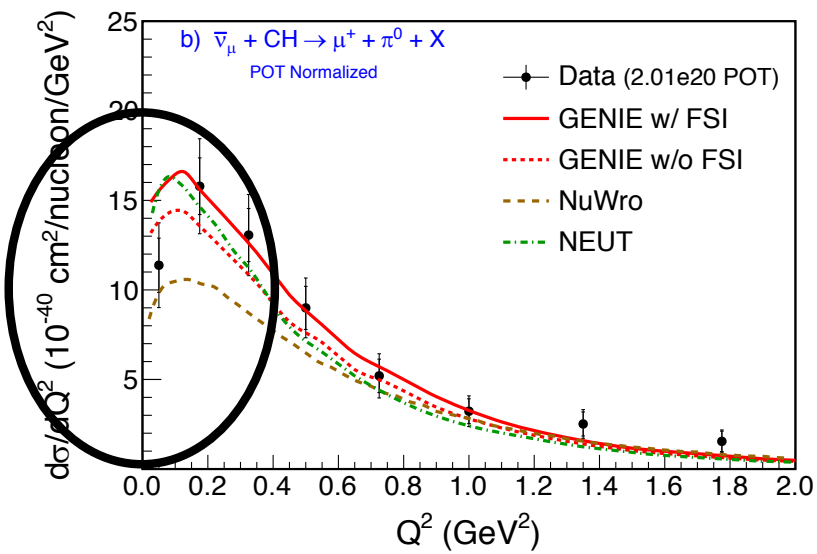
Phys. Rev. D 96, 072003 (2017)

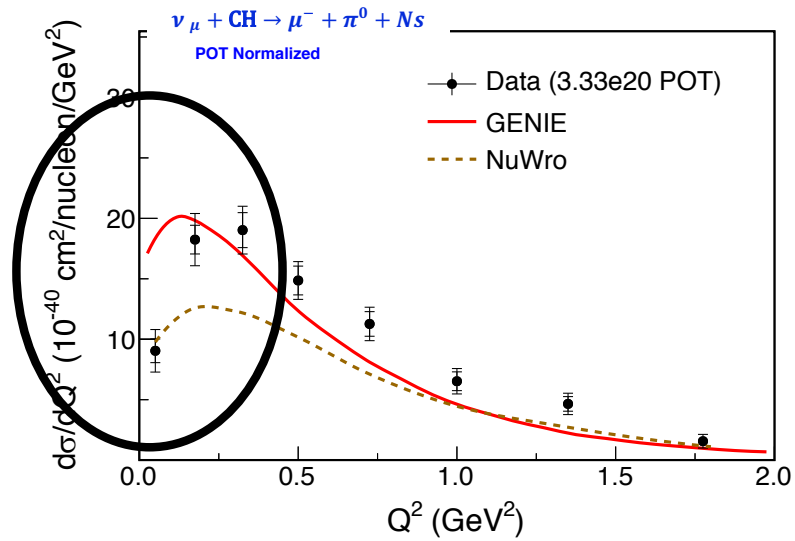
Low Q^2 suppression - RPA effect for resonances

π^0 production wants low Q^2 reduction, π^+ production not so much??









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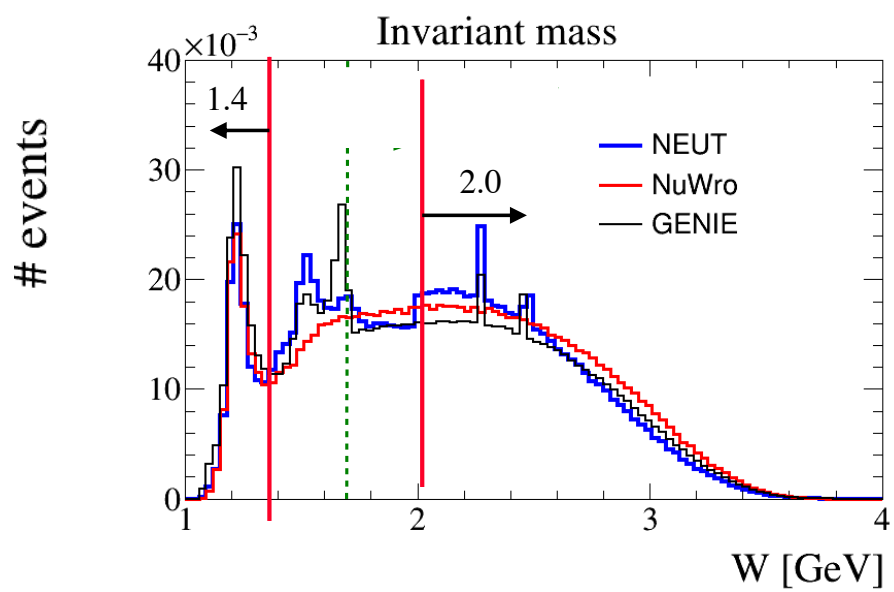
- **Above the Delta (W > 1.4 GeV) an increasingly dark and dangerous place full of unknowns. *Over 50% of the DUNE events in this region!* Multi pion resonances unknown exp. and theory!**
  - Duality works differently for neutrinos compared to electron scattering?
  - What about the interaction of duality with non-perturbative QCD effects (target mass and higher twist…)?
  - Are there different nPDFs for ν-A compared to e/μ □ A?

The General Landscape of Shallow-Inelastic Scattering Comparison of Generators

- By far the majority of contemporary studies in ν-nucleus interactions have been of QE and Δ production that is W ≤ 1.4 GeV
- However, there is plenty of activity going on above this W cut! For example with a 6 GeV ν on Fe – excluding QE.
- This region includes a series of higher mass resonances that dwindle in number as W increases.
- Since ***over 45% of the DUNE events*** have W greater than 1.6 GeV), we need to consider what we do(little)/do-not(big) know about this region!



C. Bronner- 2016
6 GeV ν on Fe

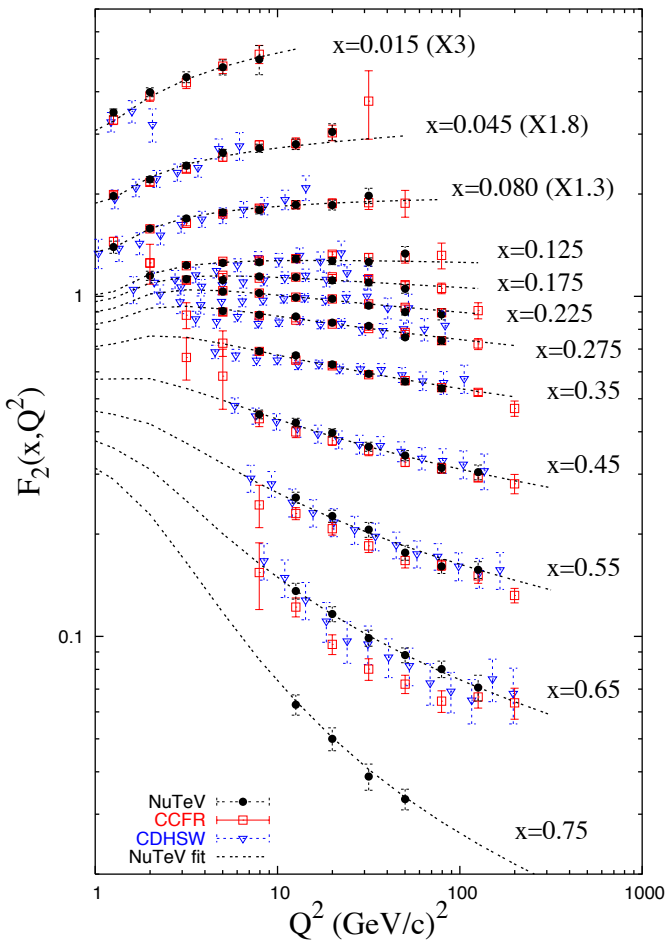
So let's start detailed examination of this region with **Deep-Inelastic Scattering** ($Q^2 > 1$ GeV^2 and $W > 2$ GeV)

Most "Recent" DIS Experiments

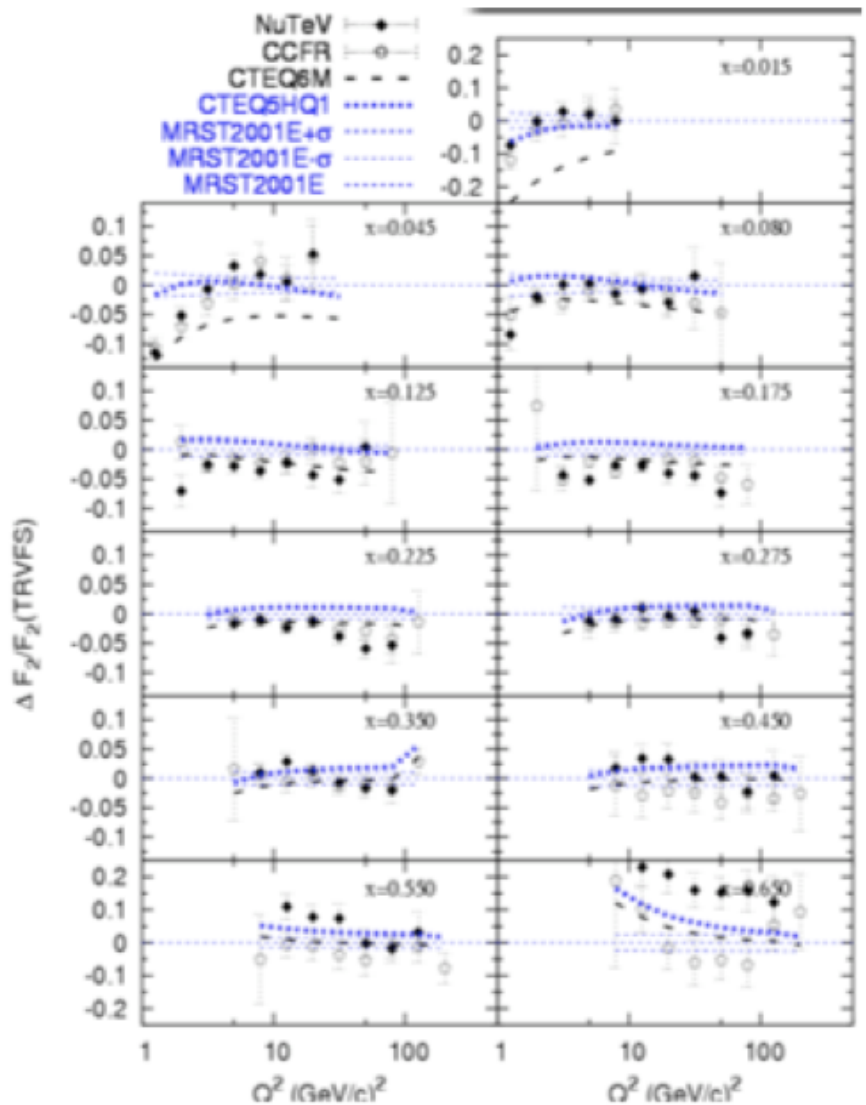
MINERvA is not a "DIS experiment" but can/will contribute to DIS studies.

	E_ν range (< E_ν>)(GeV)	Run	Target A	E_μ scale	E_{HAD} scale	Detector
NuTeV CCFR	30-360(120)	96-97	Fe	0.7%	0.43%	Coarse
NOMAD	10-200(27)	95-98	Various (mainly C)	--	---	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINERvA	2 – 50(6)	10-20	He, C, O, CH, Fe, Pb	2.1-3.2%		Finer-grained

NuTeV Structure Function F_2 Measurement on Fe (Similar results for xF_3)



- Comparison of NuTeV F_2 with global fits



- At *x>0.5* NuTeV is systematically above CCFR
- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

Summary of NuTeV ν Scattering Results

NuTeV accumulated over 3 million neutrino / antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

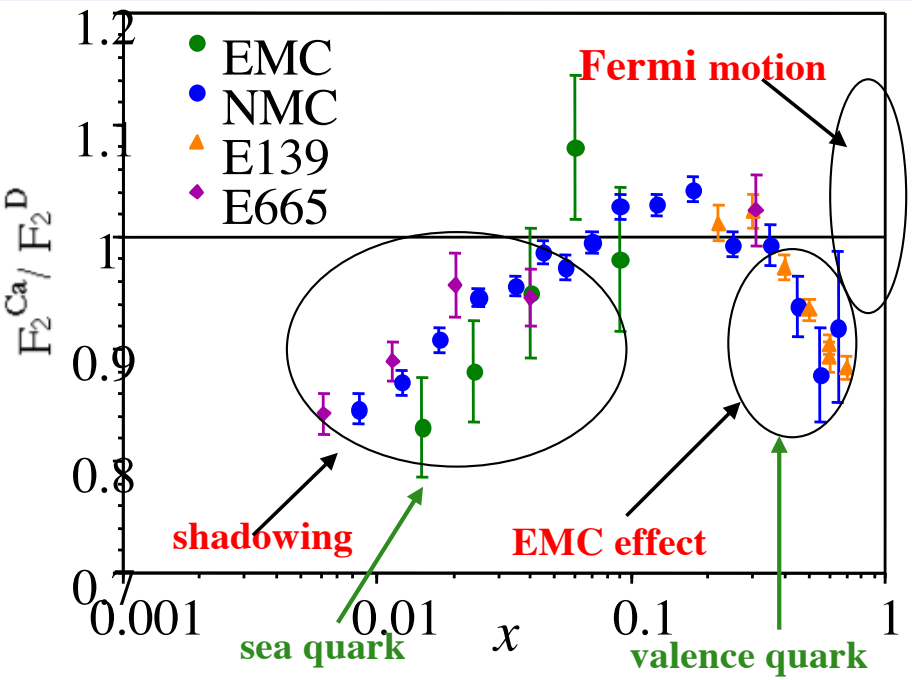
NuTeV considered over 20 systematic uncertainties and provideda full covariant error matrix.

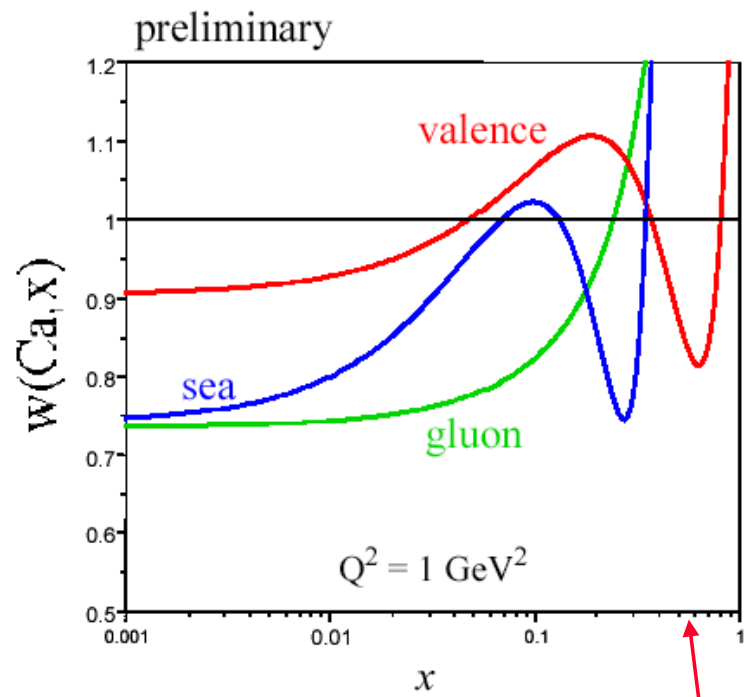
NuTeV σ agrees with other ν experiments and theory for medium x.
At low x different Q^2 dependence.
At high x (> 0.5) NuTeV is systematically higher.

NuTeV extracts the **strange quark** distribution via charm production using both ν and ν and gets a value of S(x)

All of the NuTeV Results are for ν – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$. Is this really the case?

Knowledge of DIS Nuclear Effects with Neutrinos: essentially NON-EXISTENT





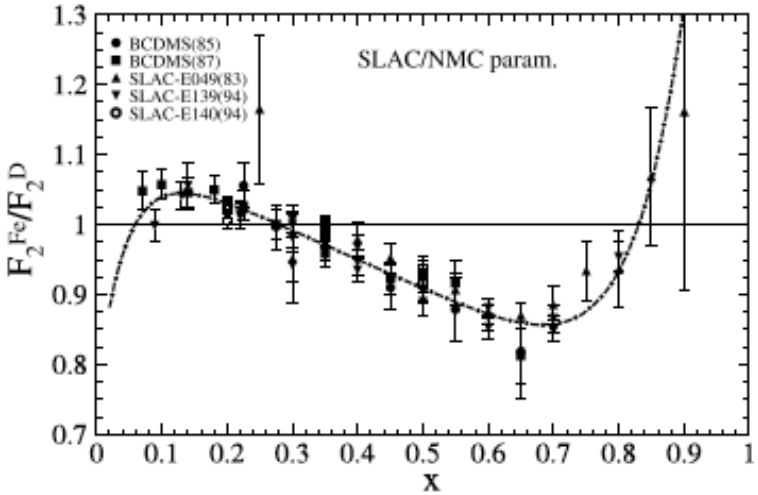
- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν – A**
- **Good reasons to consider nuclear effects are DIFFERENT in ν - A?**
  - **Presence of axial-vector current with a different coherence length than the vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**

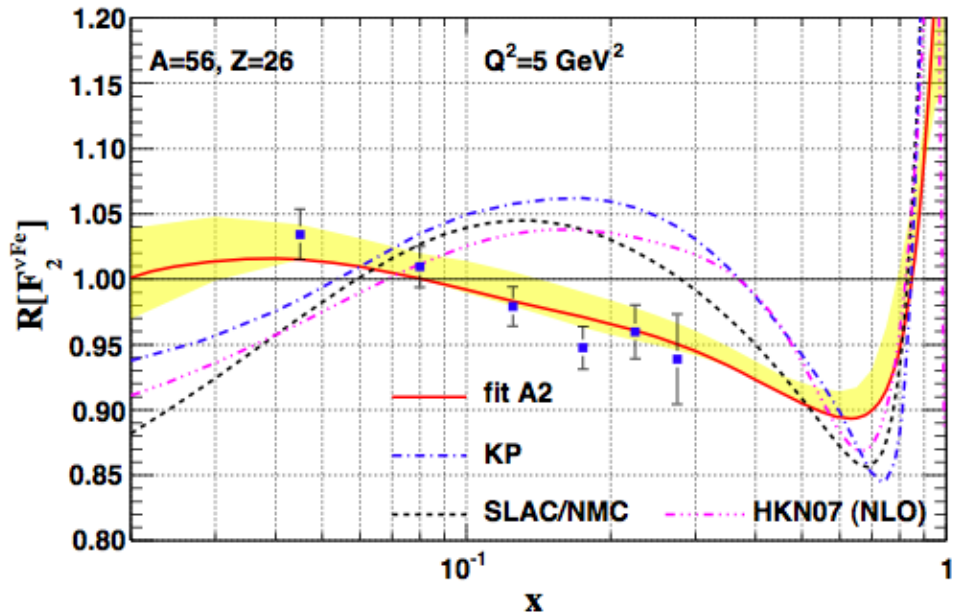
Nuclear PDFs from neutrino deep inelastic scattering

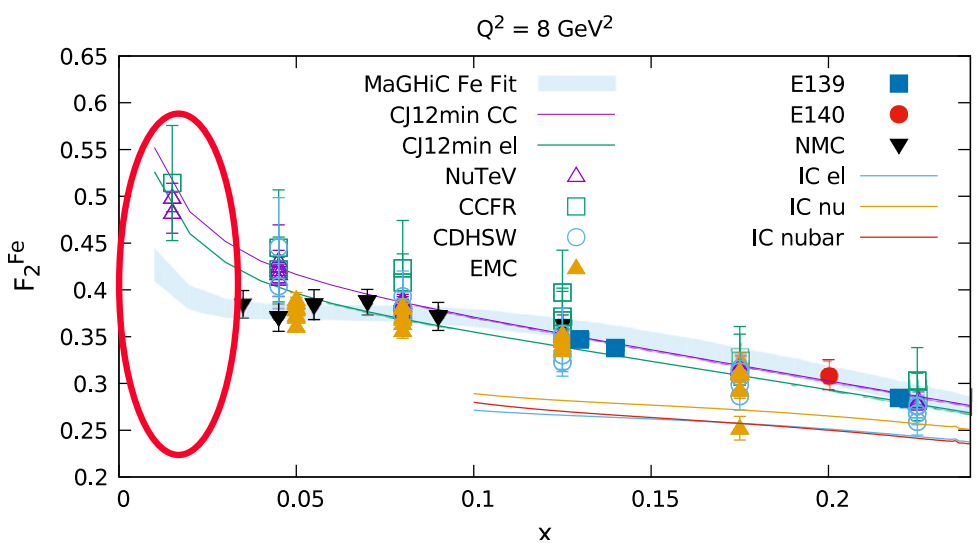
I. Schienbein (SMU & LPSC), J-Y. Yu (SMU), C. Keppel (Hampton & Jefferson Lab)
J.G.M. (Fermilab), F. Olness (SMU), J.F. Owens (Florida State U)
(nCTEQ)
Phys.Rev. D80 (2009) 094004

- Take NuTeV ν-Fe and ν-Fe as well as CHORUS ν-Pb and ν-Pb double differential cross sections. NuTeV included a full covariance error matrix.
- No ν-D, so "made" protons and neutrons from nucleon PDFs derived from a global fit to ONLY nucleon data and normalized the ν-Fe with them.
- We found **very different** nPDFs from ν-Fe compared to e/μ-Fe!
- If we use the full covariance error matrix there is no way to get a reasonable simultaneous fit to ν-Fe and e/μ-Fe results.

F_2 Structure Function Ratios: NuTeV ν-Iron





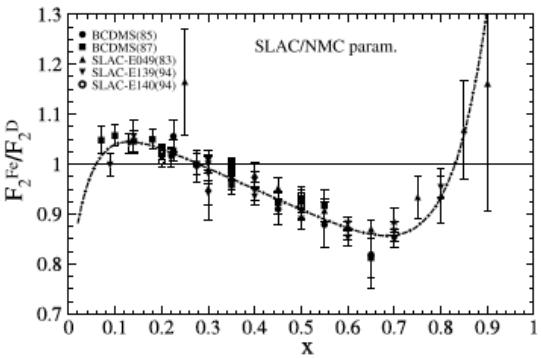


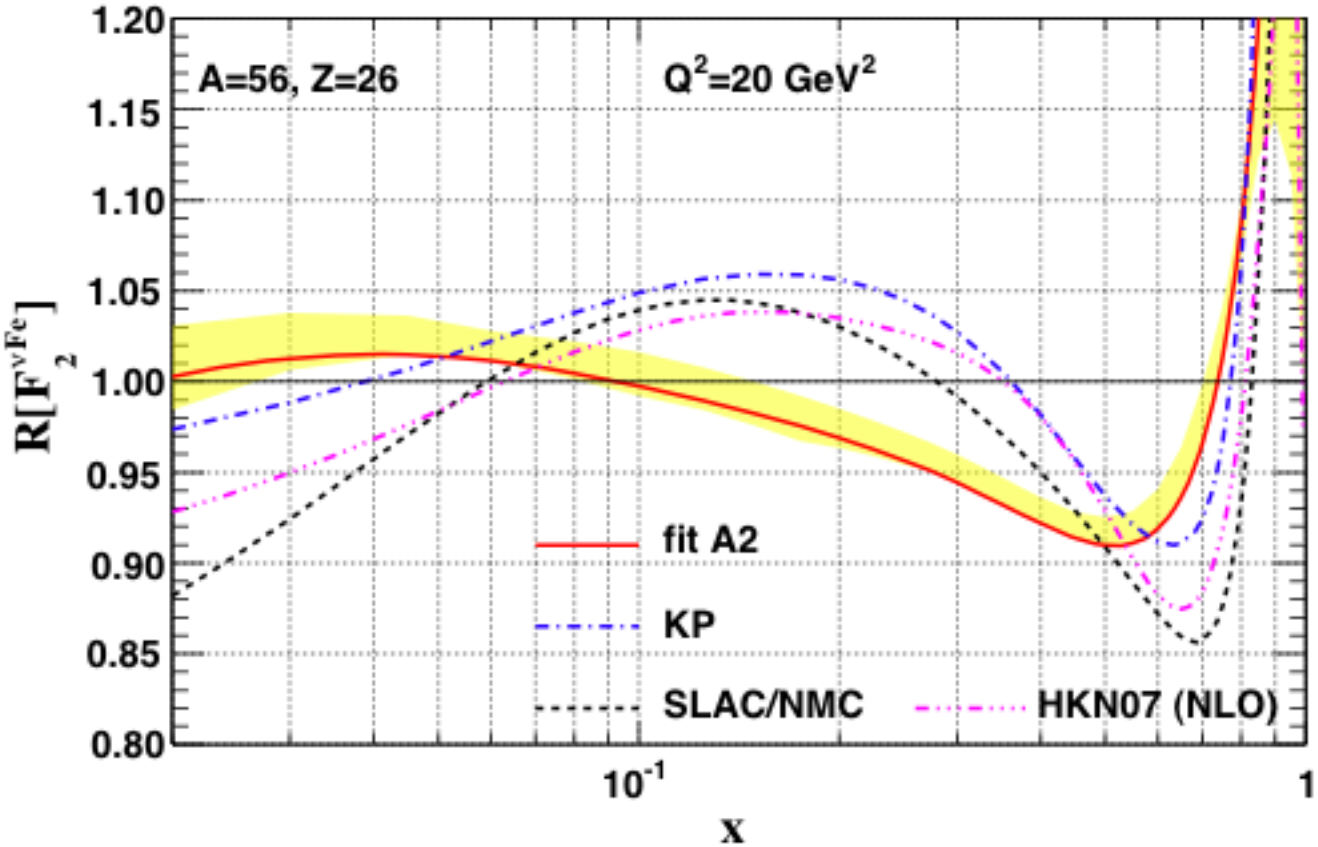
Recent Jlab analysis of F_2 from μ + Fe compared to F_2 from ν + Fe scaled by 5/18 to account for quark charges.

Narbe Kalantarians, Cynthia Keppel, M. Eric Christy

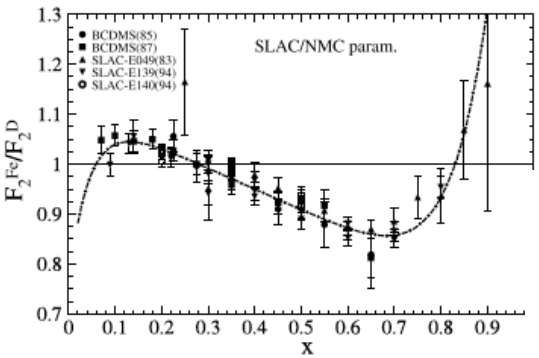
Phys.Rev. C96 (2017) no.3, 032201

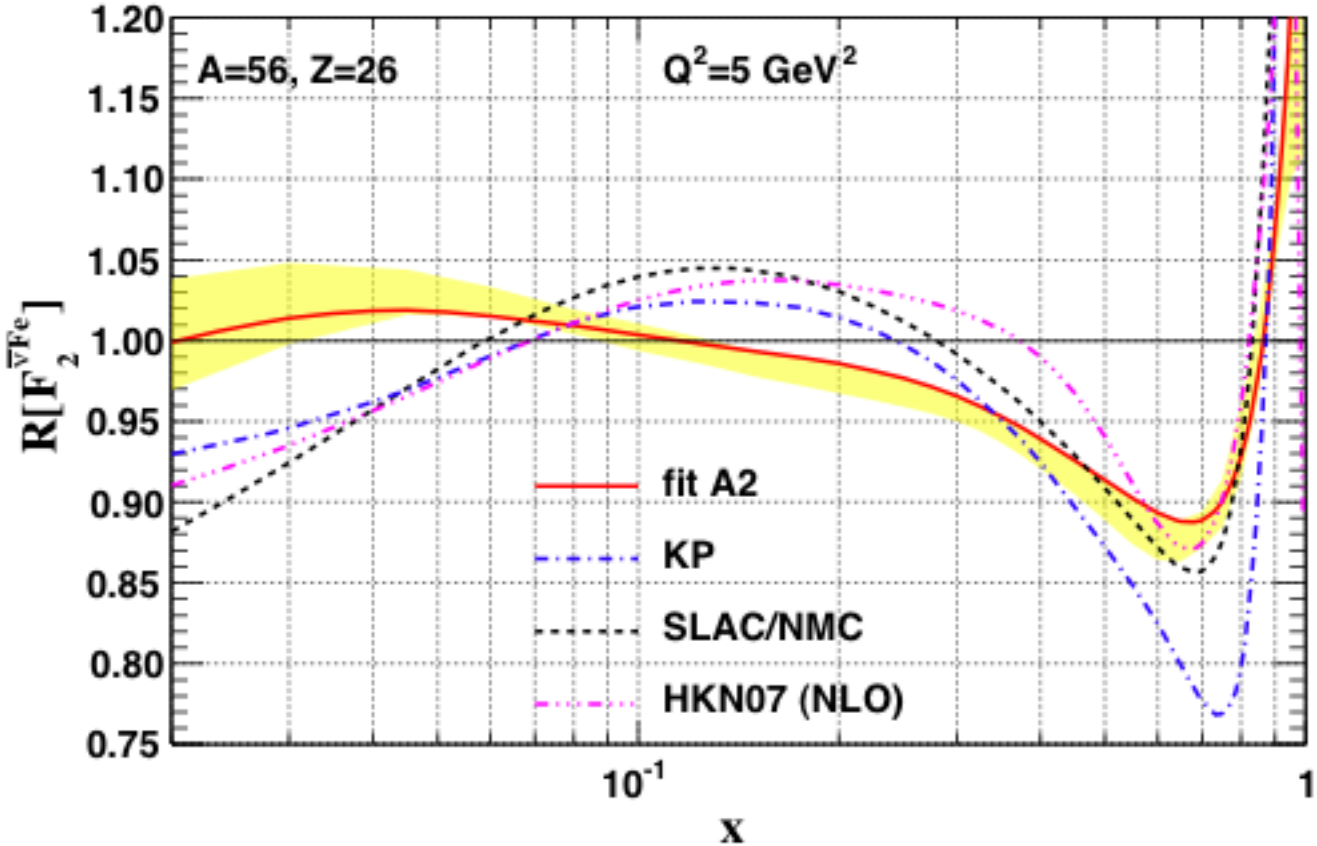
F_2 Structure Function Ratios: NuTeV ν-Iron



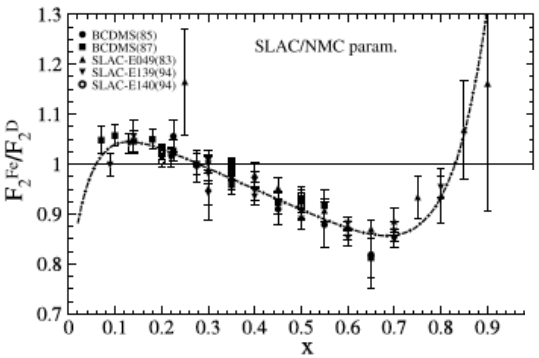


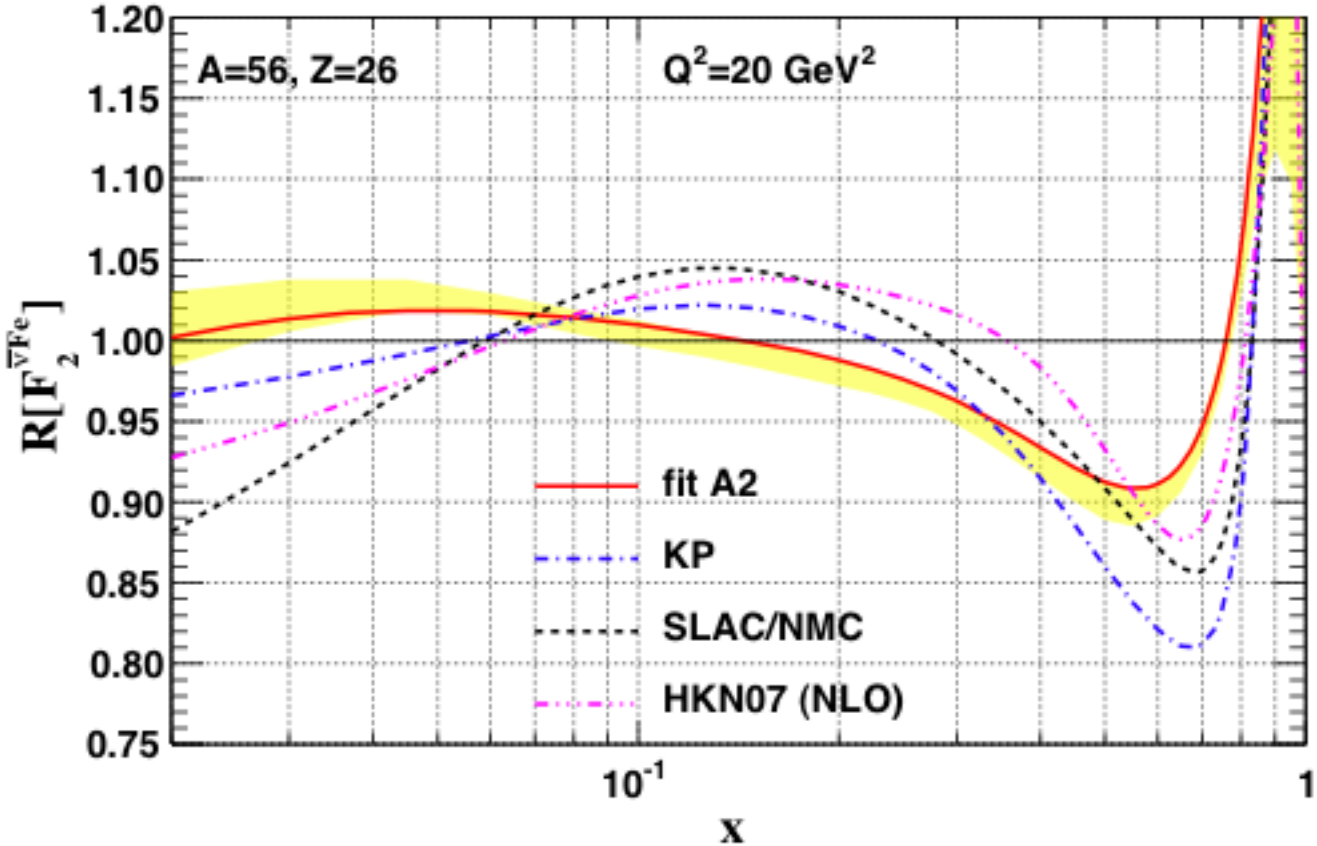
F_2 Structure Function Ratios: NuTeV $\bar{\nu}$-Iron





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





Conclusions DIS

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in global fits with nucleon data to determine nucleon PDFs.

- Current nuclear correction factors in GENIE use B-Y model that gives only ν-isoscalar Fe correction factor that is then then used for ALL nuclei.

- Nuclear correction factors (R) and, consequently, the nuclear parton distribution functions are found to be **different** for neutrino-Fe scattering compared to charged lepton-Fe. **One experiment and one nucleus. nCTEQ now taking another deeper look at this result.**

- **There is evidence that these so-called DIS partonic nuclear effects (EMC effect) continue down into the SIS region with W < 2.0 GeV!** (Low-Q scaling, duality, and the EMC effect – Arrington et al. **Phys.Rev. C73 (2006) 035205**)

- We are studying this with MINERνA using targets of C, Fe and Pb. Results published before the end pf the year

Approach the Shallow-Inelastic Scattering region

For ν unknown Experimentally and Theoretically!!

50 % of the DUNE events in the SIS + DIS region!

- Approach the SIS region from the DIS region by lowering Q and W.

- $1/Q^2$ effects - dynamic and kinematic "higher twist" terms such as the (kinematic) target mass effect. These dynamic higher twist terms are challenging in ν-nucleon and even more complicated in ν-nucleus scattering.

- No recent experimental and limited theoretical studies of these $1/Q^2$ effects with neutrinos.
  - **Twist Four Effects in Deep Inelastic Neutrino Scattering and** Sin2□Theta□wSin2□Theta□w
    S. Fajfer, R.J. Oakes (Sarajevo U. & Northwestern U. & Fermilab). 1985. 2 pp.
    Published in **Fermilab Batavia - FERMILAB-CONF-85-102-T (85,REC.AUG.) 4p**
  - **Twist Four Corrections to Charged and Neutral Current Neutrino Scattering**
    P. Castorina, P.J. Mulders (MIT, LNS). Jun 1984. 16 pp.
    Published in **Phys.Rev. D31 (1985) 2753**
  - **ννN, μμN interactions: Structure functions, higher twist**
    C. Matteuzzi (SLAC). Oct 1981. 13 pp.
    Published in **AIP Conf.Proc. 81 (1982) 186-198**

- Continuing down in W we eventually hit resonances and instead of speaking of quarks and gluons we start speaking of nucleons and pions! The physics is continuous so there should be a common **"quark language = hadron language"** → **quark-hadron duality!**

“Duality”

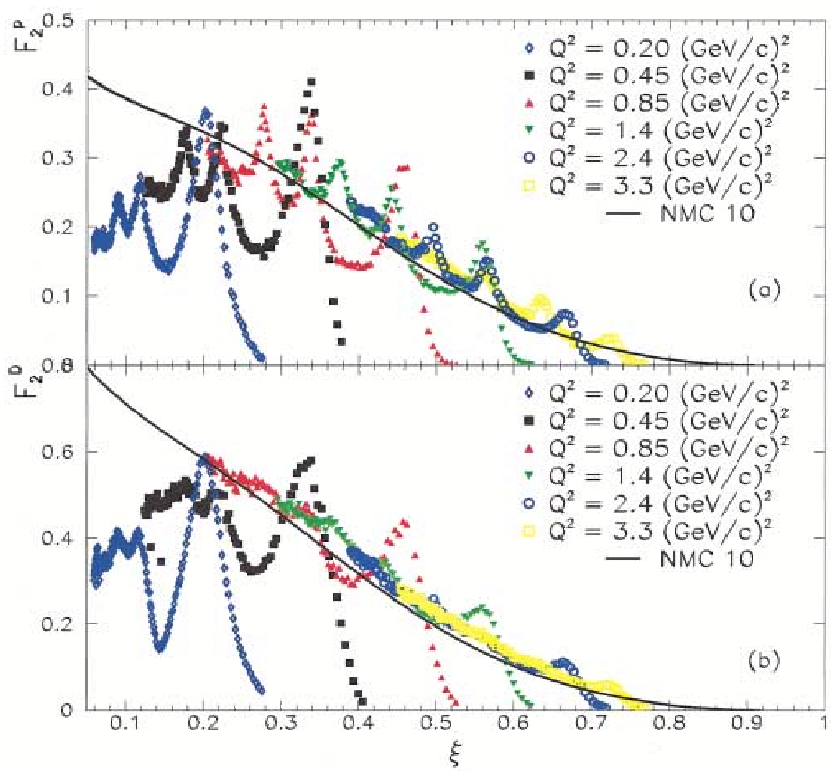
- Relationships between meson–hadron and quark–gluon degrees of freedom.
- Quark–hadron duality is a general feature of strongly interacting landscape.
- There exist examples where low-energy hadronic phenomena, averaged over appropriate energy intervals, closely resemble those at higher energies, calculated in terms of quark-gluon degrees of freedom.
- Duality is an important ingredient for the Bodek-Yang model that the neutrino event generators GENIE, NEUT, NuWro employ.
- Originally studied and confirmed in e-N scattering – how about ν-N scattering? There is essentially no high-statistics ν-N experimental data with W>1.4 GEV for tests! Rely on **models** for resonances and essentially **ONE** theoretical look at duality in ν-N scattering.

Duality HOLDS in electron–nucleon scattering!

What does that mean?

- If you take F_2 determined from a QCD fit to DIS data and extrapolate down in ξ - a form of x_{Bj} that compensates for low-Q phenomena. The extrapolation runs approximately through the middle of the resonances.

$$\xi = \frac{2x}{(1+\sqrt{1+4m_N^2x^2/Q^2})}$$



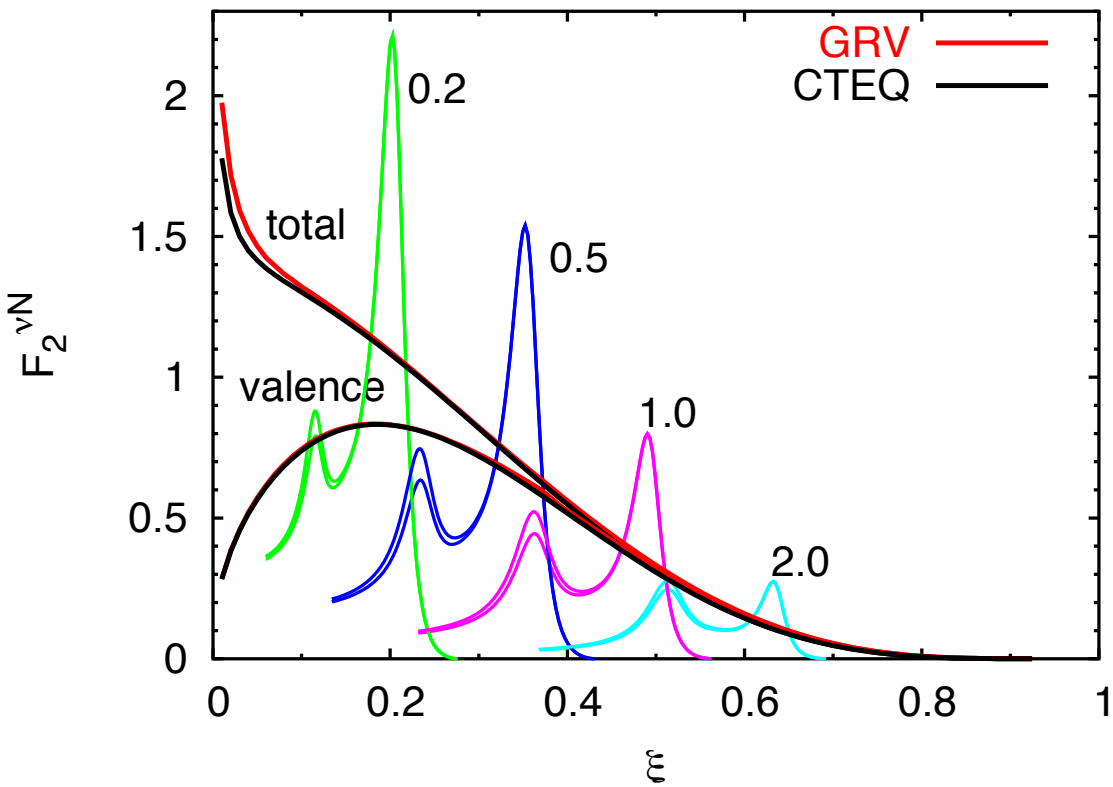
JLAB: recent experimental data on F_2 of the reactions $ep \to eX$, $eD \to DX$ in the resonance region

solid curve — global fit to the world's DIS data by NMC collaboration

The data at various values of Q^2 and W average to a smooth curve if expressed in terms of ξ.

From work of Olga Lalakulich – **a real expert on ν-N duality who left the field – Luckily we still have Manny Paschos retired and Wally Melnitchouk - busy** –

Duality supposedly holds for the averaged neutrino $F_2^N = (F_2^n + F_2^p) / 2$



What about individually ν-n and ν-p scattering?

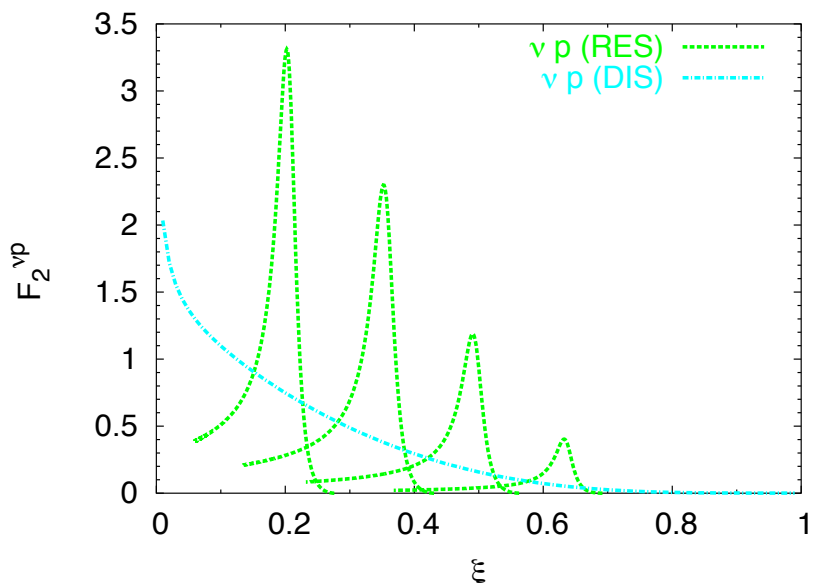
Resonance estimates from Lalakulich, Melnitchouk and Paschos

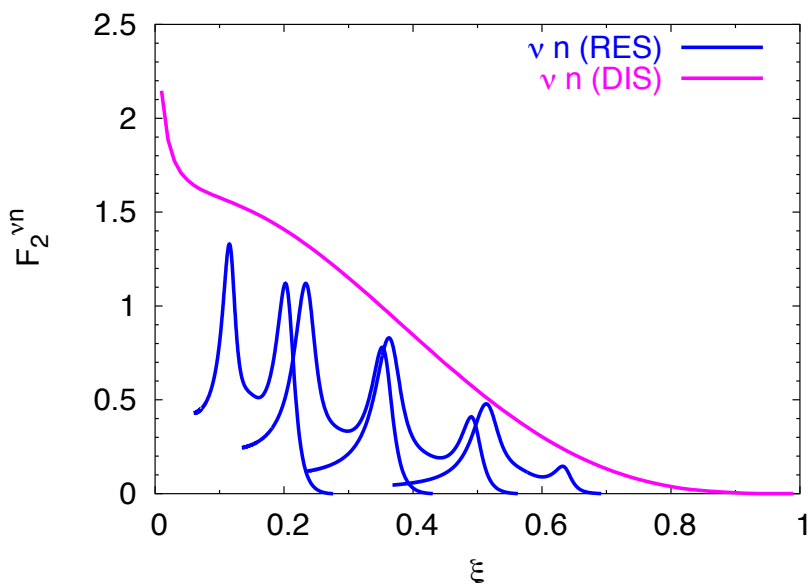
Oops!

Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

$$F_2^{\nu p(res-3/2)} = 3F_2^{\nu n(res-3/2)}$$
$$F_2^{\nu p(res-1/2)} \equiv 0$$

$F_2^{\nu n(res)}$: finite contributions from isispin-3/2 and -1/2 resonances

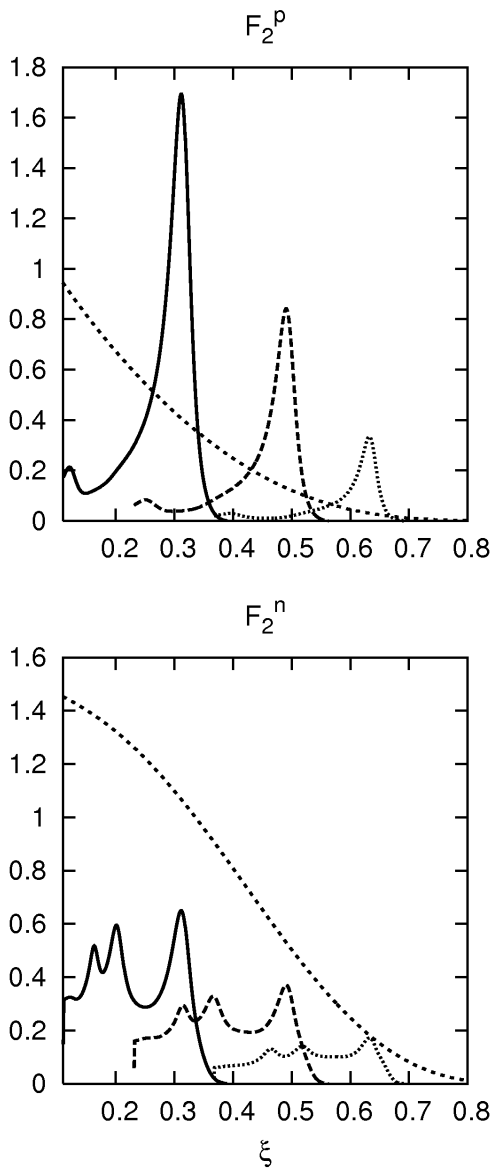




Also does not hold for n and p individually

when using the Rein-Sehgal Model for ν-N Resonances

WARNING: R-S model questionable



Similar results in the framework of Rein–Sehgal Model Graczyk, Juszczak, Sobczyk, Nucl Phys A781 (19 resonances included in the model)

$P_{33}(1232)$,
$P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$,
$P_{33}(1600)$,
$S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$

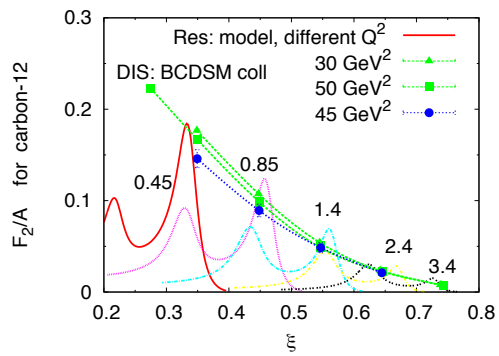
Interplay between the resonances with different isospins:

isospin-3/2 resonances give strength to the proton structure functions, while isospin-1/2 resonances contribute to the neutron structure function only

However, it is a different story when talking of NUCLEI not NUCLEON

Even with the carbon nucleus (equal p and n) duality with both incoming electrons and neutrinos has challenges

For nuclei, the Fermi motion and other medium effects broaden resonances, thus performing averaging



Resonance structure functions: isobar model with phenominological form factors OL,Paschos, PRD 71, 74 includes the first four low-lying baryon resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

Preliminary!

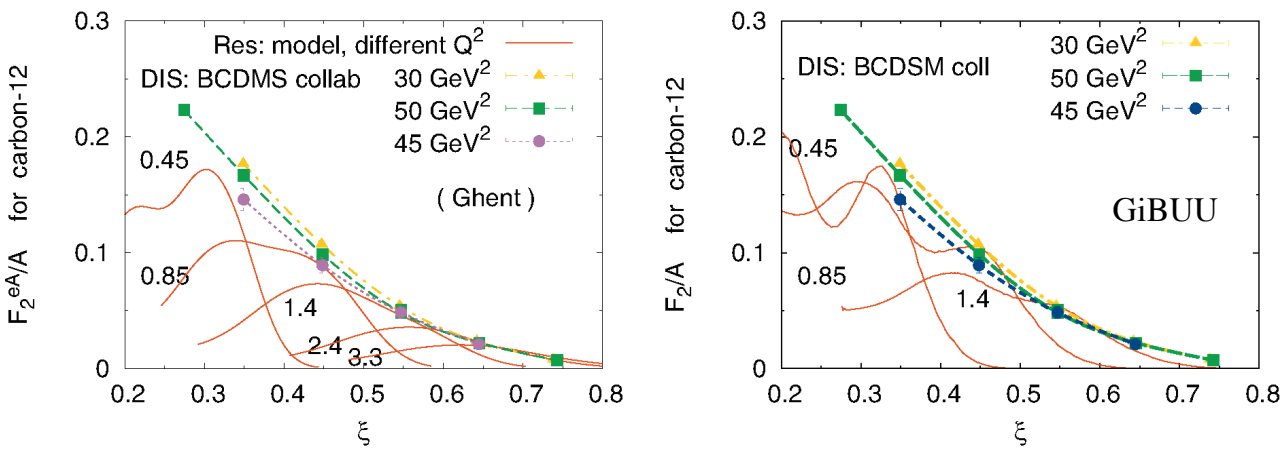


FIGURE 3. (Color online) Resonance curves $F_2^{e^{12}C}/12$ as a function of ξ, for $Q^2 = 0.45, 0.85, 1.4, 2.4$ and 3.3 GeV^2 (indicated on the spectra), obtained within Ghent (left) and Giessen (right) models, compared with the experimental data [23, 24] in the DIS region at $Q^2_{DIS} = 30$, 45 and 50 GeV^2.

However, it is a different story when talking of NUCLEI not NUCLEON – now Fe

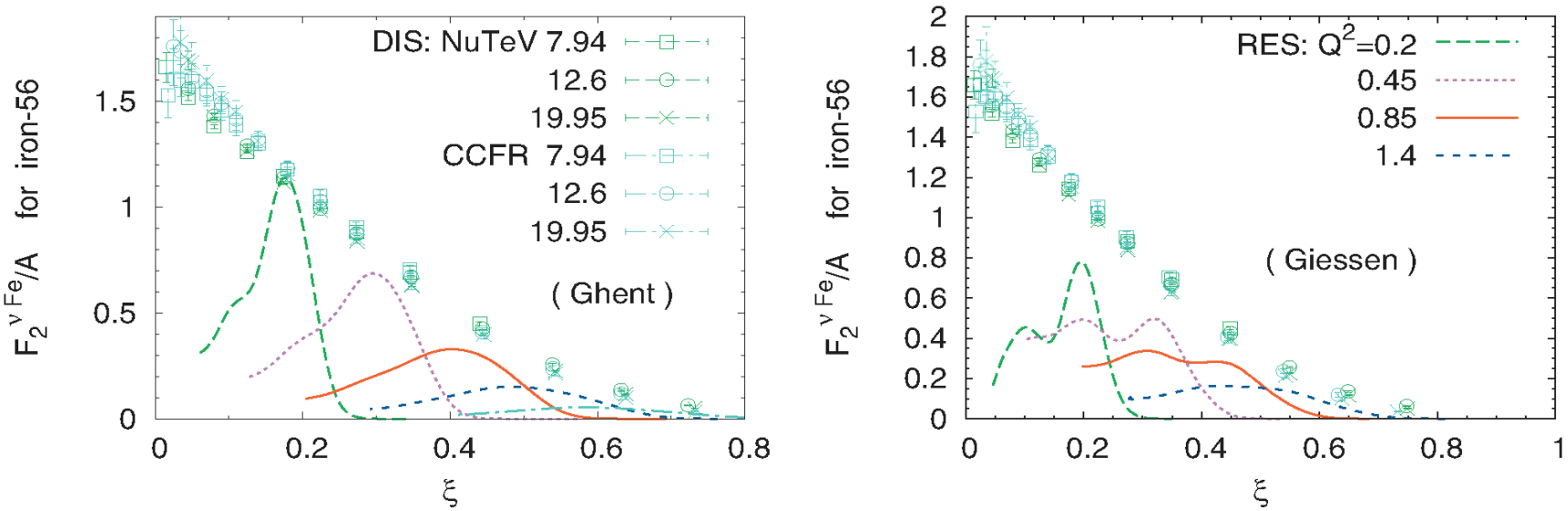


FIGURE 5. (color online) The computed resonance curves $F_2^{\nu\,^{56}Fe}/56$ as a function of ξ, calculated within Ghent(left) and Giessen (right) models for $Q^2 = 0.2, 0.45, 0.85,\ 1.4,$ and $2.4\ \mathrm{GeV}^2$. The calculations are compared with the DIS data from Refs. [26, 27]. The DIS data refer to measurements at $Q^2_{DIS} = 7.94$, 12.6 and 19.95 GeV^2.

- $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering duality does NOT hold for proton and neutron individually
- $F_2^{\nu p\ \nu n}$: Duality HOLDS for the averaged structure functions. Need equal number of neutrons and protons…
- Duality does not seem to work for nuclei at all…

Summary and Conclusions – SIS and DIS

- There are significant differences in the measurement of ν DIS (nuclear) structure functions by different experiments that must be resolved.
- There are indications from **one** experiment using **one** nucleus that **ν and $\bar{\nu}$ -induced partonic nuclear effects are different** than found by $\ell^{\pm}$-A experiments.
- Need a systematic **experimental** study of **ν-induced partonic nuclear effects.**
- Need careful **experimental and theoretical** examination of higher W (above the Δ) **single and multi-pion production.**
- **Need to carefully understand the concept of "duality" as exhibited by ν and $\bar{\nu}$ on nuclei and how this co-exists with non-perturbative QCD effects! Generator behavior in the SIS region uses this concept.**
- **We have now reviewed the full W landscape of neutrino results compared to the nuclear models in our event generators and…**

In Summary: Nuclear Physics Meets Neutrino Physics

We have no single nuclear model that comes close to fitting all of the accumulated data!
However it is improving….

It is not a knockout – we are simply "on the ropes".
There has been increasing collaboration between the HEP and NP communities that has been essential for the progress we have made. We need MORE!

Conclusions across the full W range.

- Need to move away from the simple FG 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 nucleON scattering measurements to constrain the nuclear model. **NP-HEP-AstroPart. Collaborations!**
- Need highly accurate neutrino nucleus scattering measurements to constrain the nuclear model. **NP-HEP Collaborations!**

Do you want to continue addressing the mysteries of SIS and DIS Scattering?

NuSTEC Workshop on Shallow- and Deep-Inelastic Scattering

11-13 October, Gran Sasso Science Institute, L'Aquila, Italy

1) **General introduction and considerations from non-neutrino communities.**
   - A) Introduction to SIS/DIS Theory and Models – A. Friedland
   - B) e-A community studies of the SIS/DIS region – C. Keppel

2) **Generator / Transport treatments of the SIS and DIS region.**
   - A) Improved Rein-Sehgal Model above the Delta – S. Dytman
   - B) Status of the Bodek-Yang Model – U. Yang
   - C) Generator/Transport Treatments:
     - GiBUU – K. Gallmeister
     - GENIE – J. Tena Vidal
     - NEUT - C. Bronner
     - NuWRO – J. Sobczyk
   - D) Overview: Generator Comparison of SIS/DIS treatment – C. Bronner

3) **Sensitivity of oscillation parameters to the SIS and DIS region.**
   - A) NOvA – M. Muether
   - B) Atmospheric Neutrino Studies, SK and HK – C. Bronner

4) **Resonant and non-resonant pion production with W > Delta**
   - A) Isobar models of resonance production - TBD
   - B) Dynamical coupled-channel models – S. Nakamura
   - C) Non-resonant and interference effects in pion production – M. Kabirnezhad
   - D) Experimental nu-A higher-W pion production studies – S. Dytman

5) **The transition from SIS to DIS**
   - A) Duality in e-nucleon / nucleus scattering – E. Christy
   - B) Duality in neutrino nucleus scattering - E. Paschos
   - C) Higher Twist and Duality in the SIS/DIS transition – H. Haider
   - D) Chiral Field and Regge theory in the transition region - N. Jachowicz

6) **Nuclear modifications of structure functions and nuclear PDFs**
   - A) Nuclear Medium Effects on Structure Functions I – S. Athar
   - B) Nuclear Medium Effects on Structure Functions II – S. Kulagin
   - C) nPDFs from e/mu-A and nu-A scattering – A. Kusina
   - D) MINERvA results of Inclusive and DIS on nuclear targets – A. Norrick

7) **Hadronization in the nuclear environment**
   - A) Hadronization models in neutrino event generators – T. Katori
   - B) The GENIE Hadronization Model – C. Andreopoulos
   - C) Hadronization in FLUKA – P. Sala
   - D) The Lund Hadronization Model - S. Prestel

8) **Roundtable / Final Discussion**
   - Getting this information into generators

Summary and Conclusions

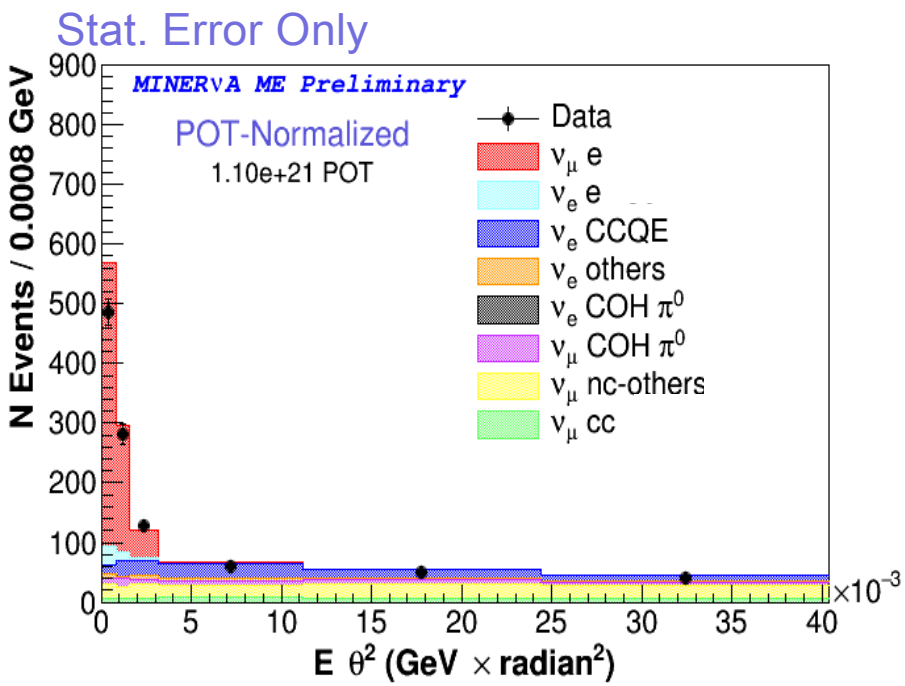
- Nuclear effects, present in the data of all contemporary neutrino oscillation experiments, mixes topologies and changes energy between produced and (detected)final states.
- The precision with which neutrino properties can be extracted from oscillation experiments is clearly limited by the quality of the nuclear model used.
- The nuclear model 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 refine the scientific community, based on NP-HEP collaboration, around the question of neutrino-nucleus interactions.
- BOTH communities will benefit from this collaboration..

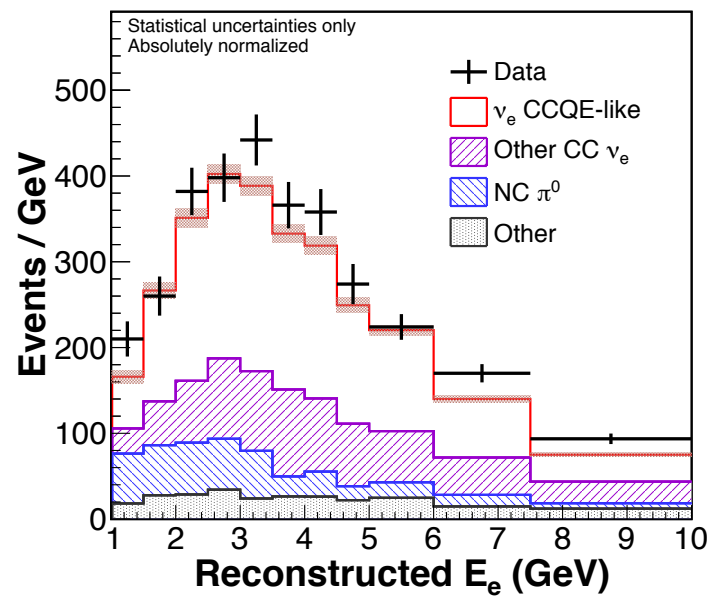
Additional Details

Final State Electrons

ν_μ + e – scattering

ν_e + n scattering

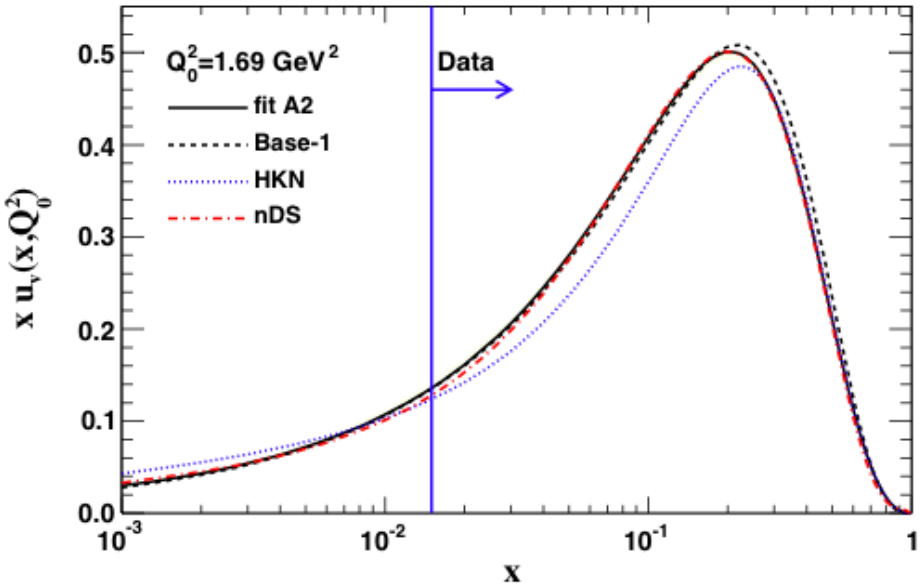


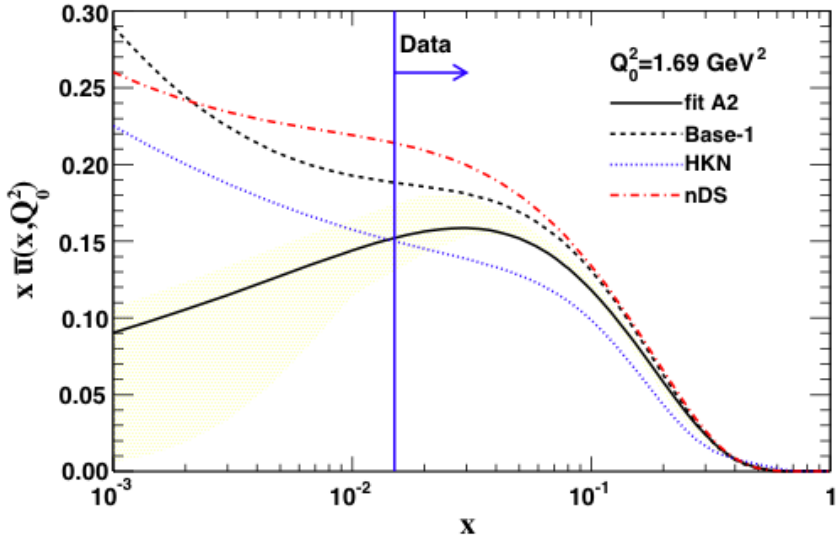


- ME sample has about **800 ν+e events**
- Flux constraint ongoing
  - changes flux uncertainty from about 8% to 6% or better in the focusing peak

- Above from LE publication: ≈ 3200 events
- **Expect over twice as many in ME exposure**
- **Note this is only CCQE-like events!**

Iron PDFs


Q_0^2=1.69 GeV^2
Data
fit A2
Base-1
HKN
nDS
$x\ u_v(x,Q_0^2)$
x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fit A2
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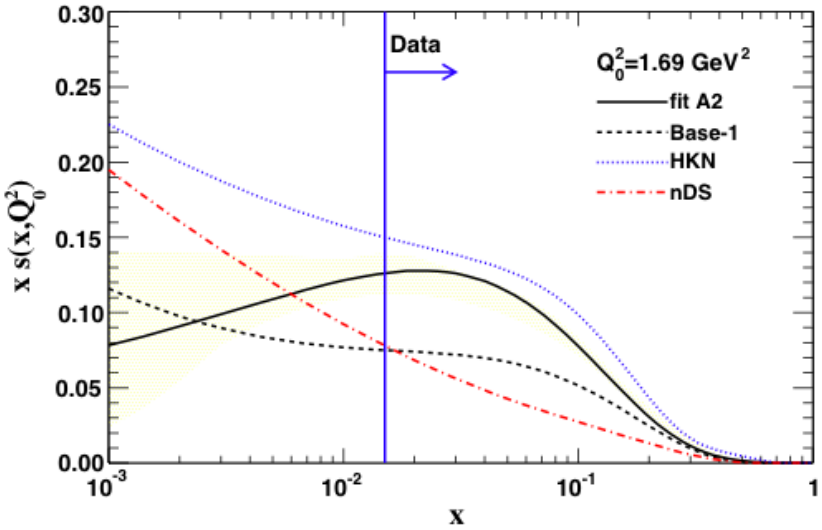
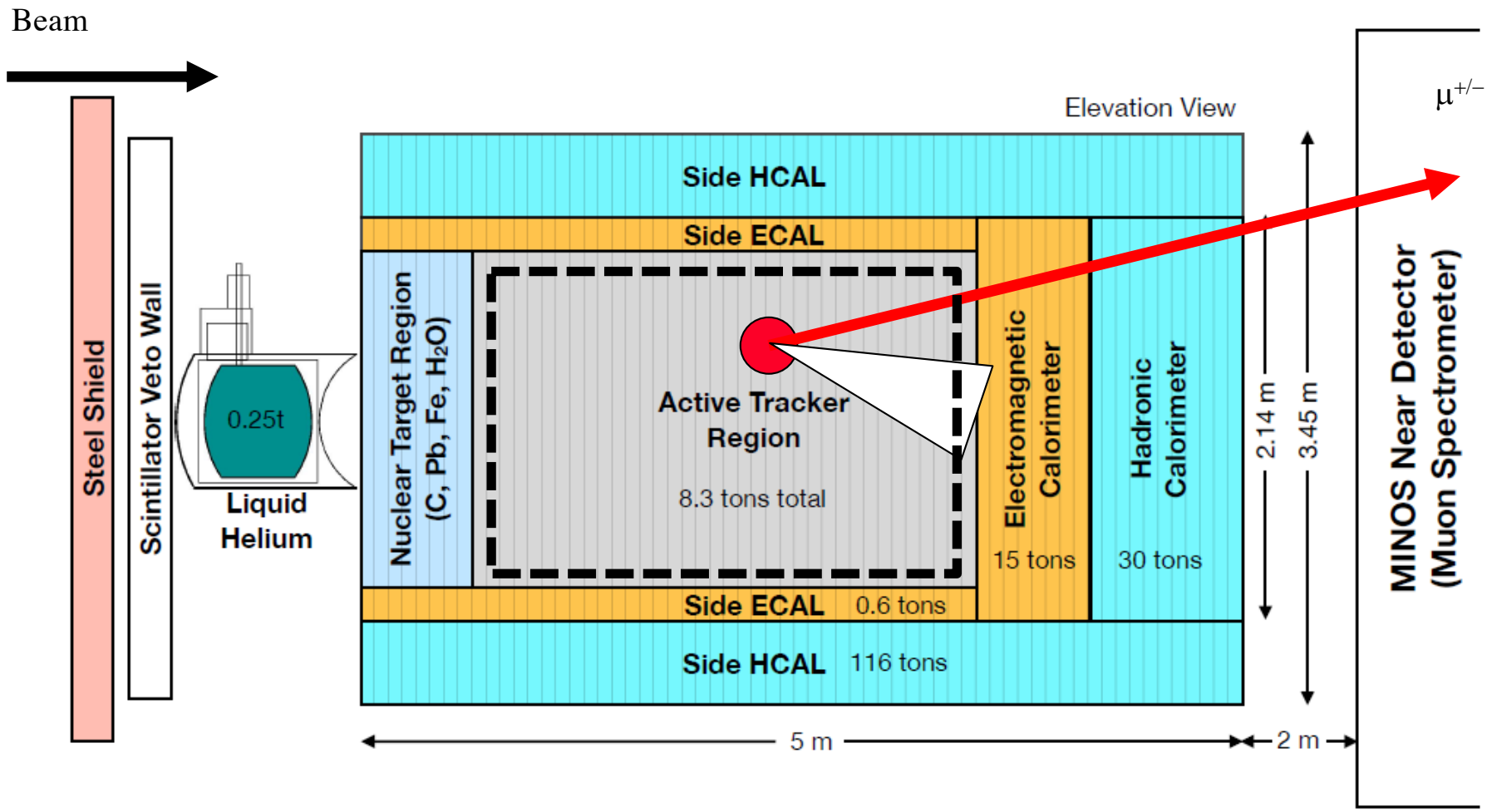
nDS
$x\ \bar{u}(x,Q_0^2)$
x


Data
Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
$x\ s(x,Q_0^2)$
x

Typical Neutrino Scattering (MINERvA) Detector

Mostly carbon, iron and lead nuclei



Neutrino Nucleus Scattering

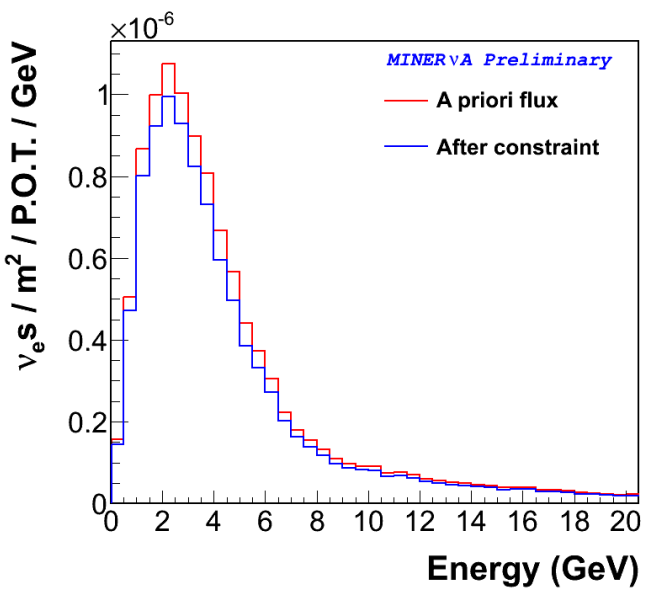
Neutrino Flux Term: $\phi_\nu(E \geq E_m)$

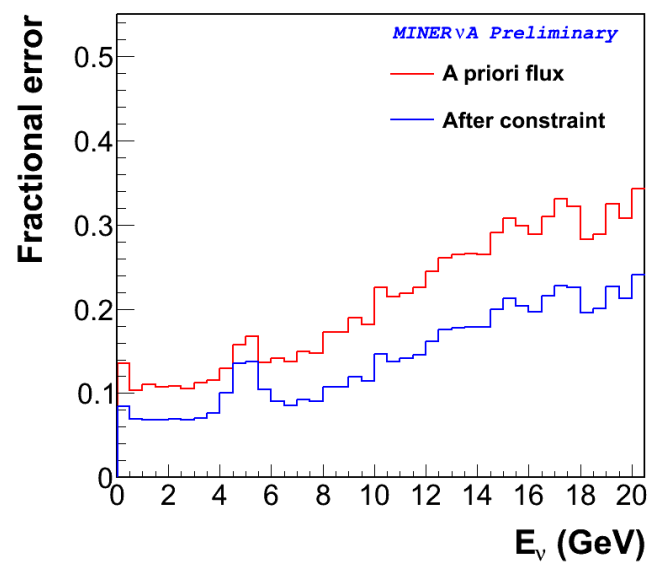
In-situ Flux Measurement: ν – e scattering

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

G_F and θ_W: well-known electroweak parameters

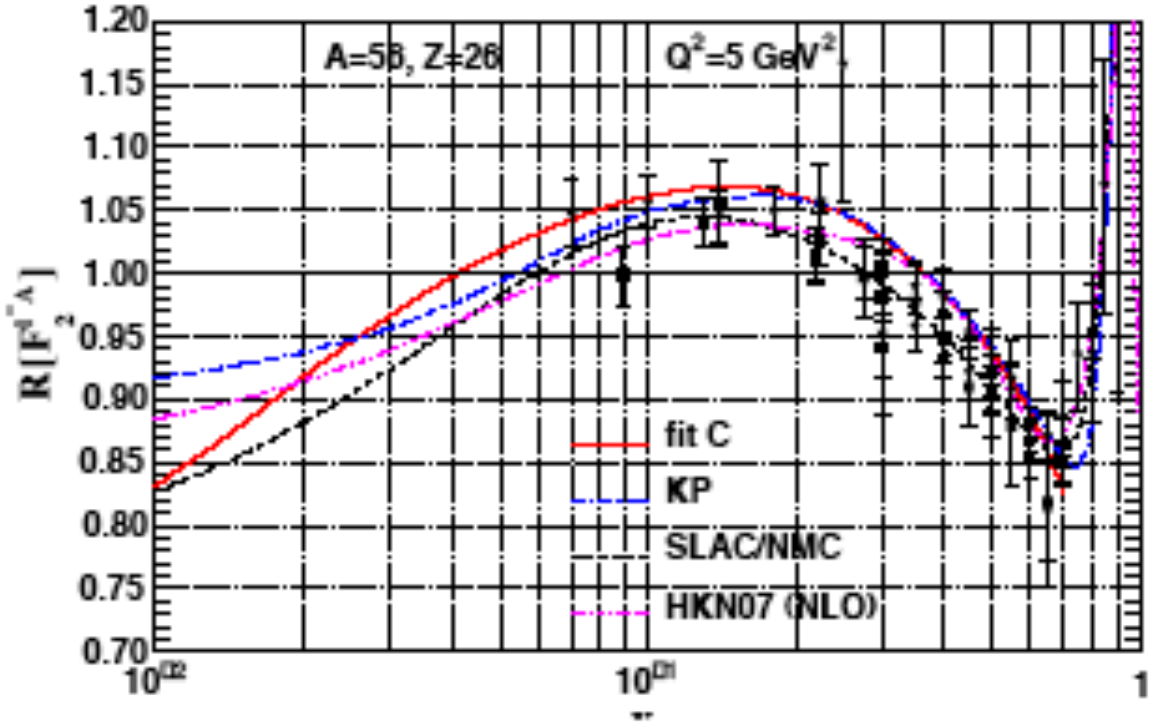
- Using ν – e results, we can apply an additional constraint to the flux
- Here, the a priori is the HP corrected flux.





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

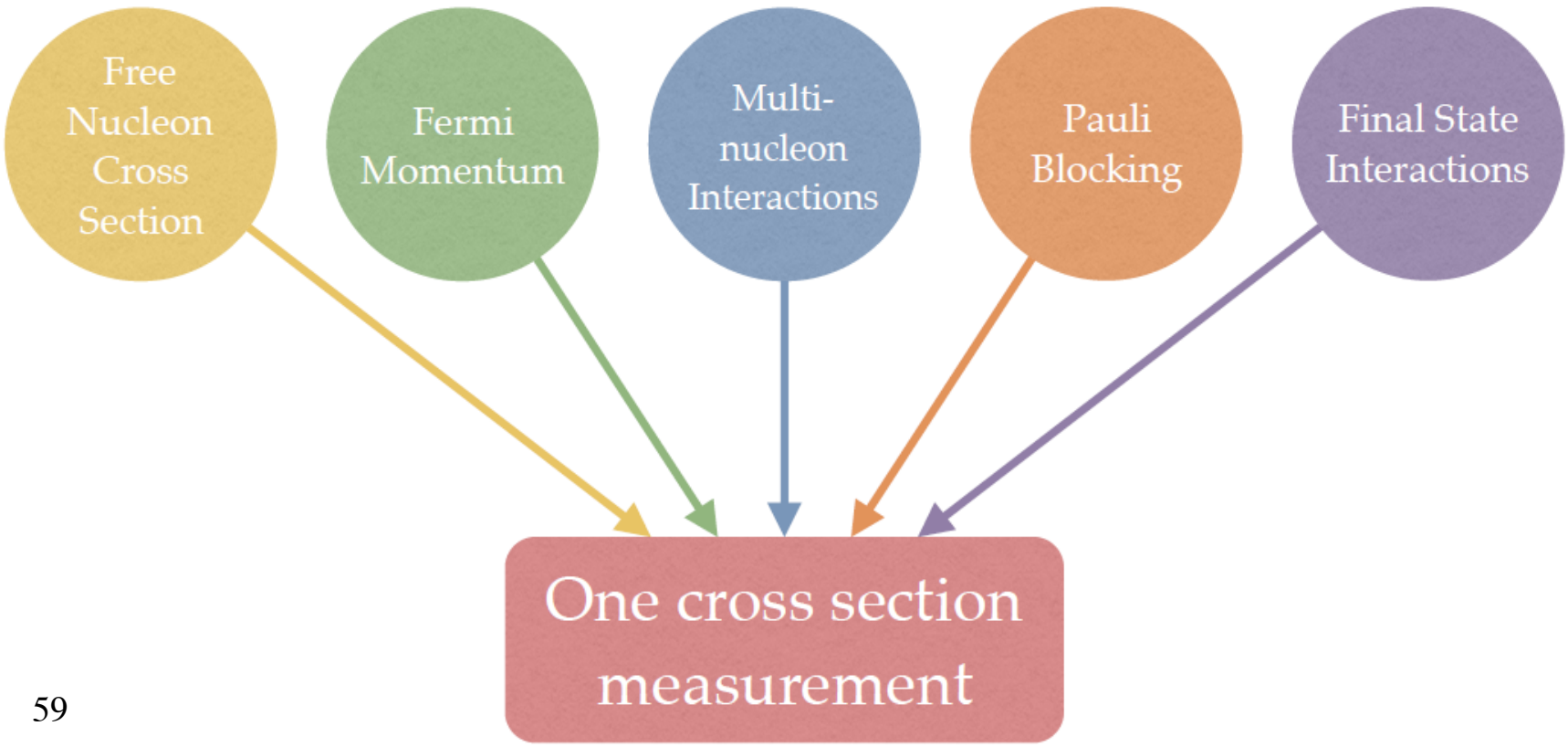
Nuclear Structure Function Corrections $\ell^{\pm}$ (Fe/D_2)



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

MINERvA Approach to Constraining the Nuclear Model

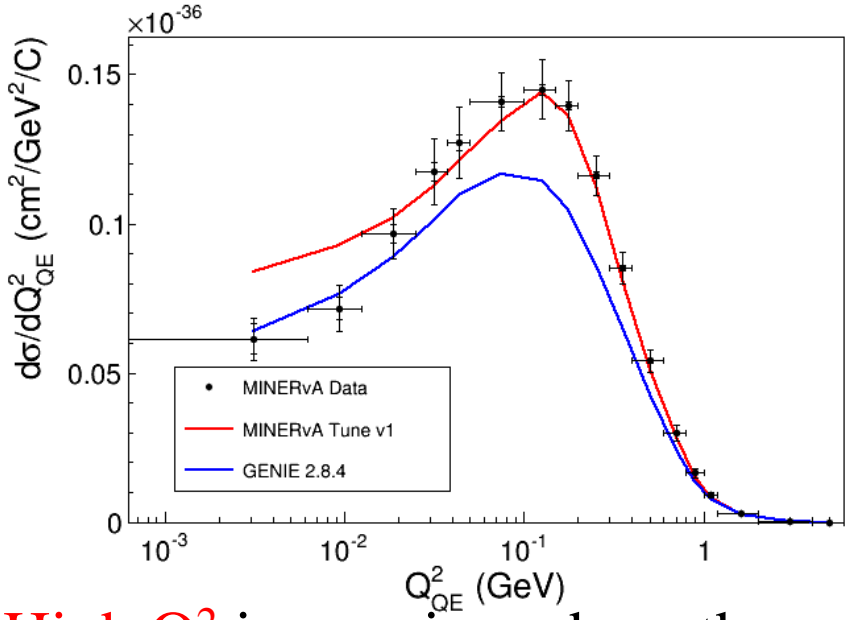
- Developing models of neutrino interactions is difficult — there are many, many unknown parameters, and we generally have to measure a bunch of them at once:

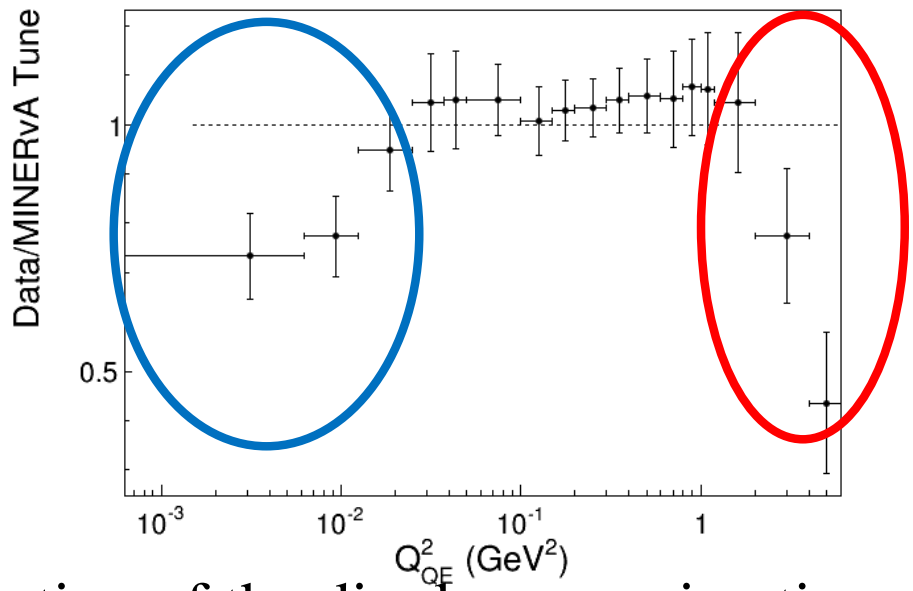


L.Fields

Where does it **not** work?

- Neutrino CCQE-like Sample



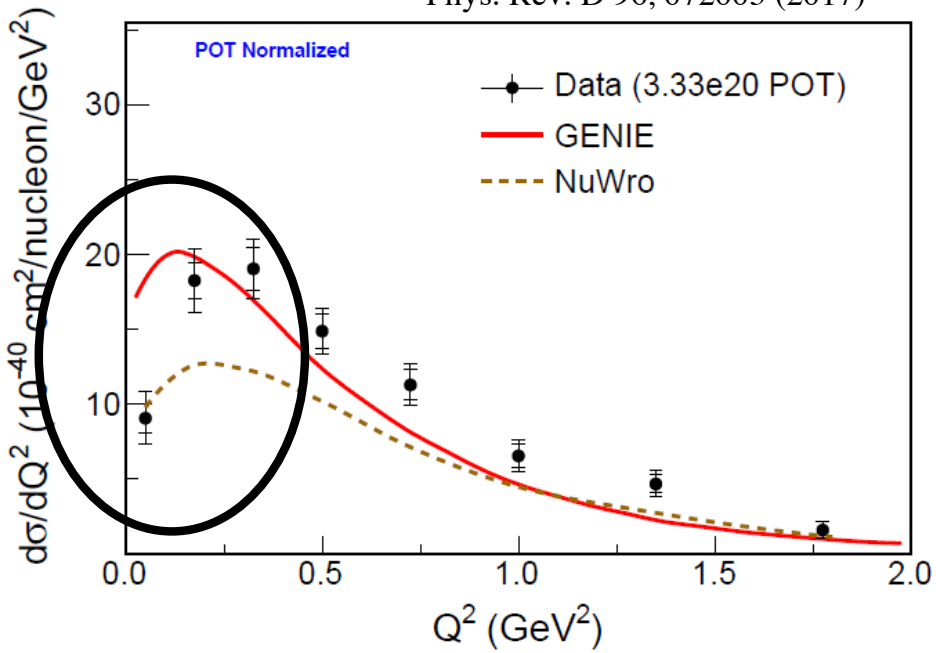


- High Q^2 is a region where the assumption of the dipole approximation starts to break down.
- Low Q^2 is a region of phase space where the fraction of events has an increased population of resonant pion qe-like events.
- Need low Q^2 reduction in resonant event production – RPA for resonances

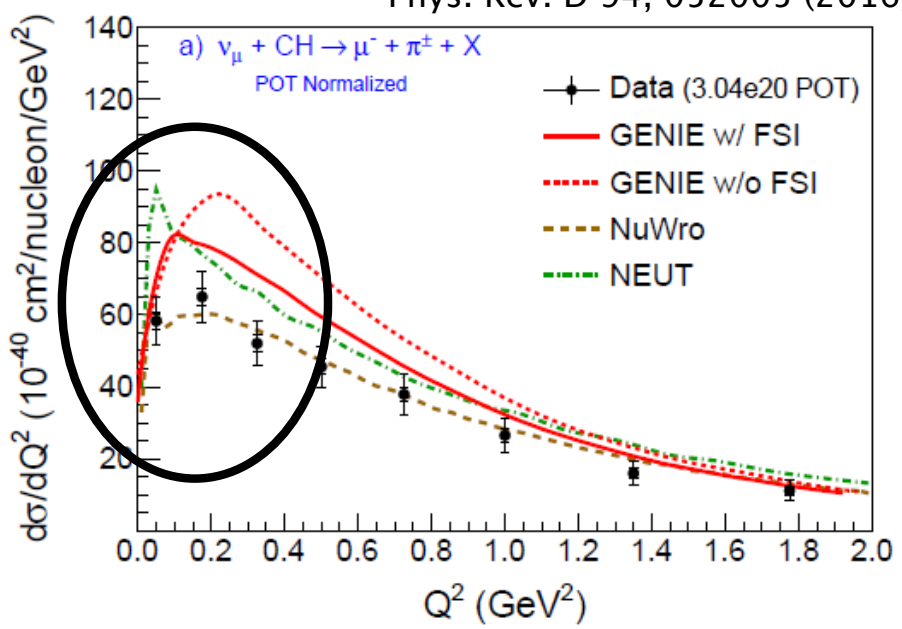
Low Q^2 reduction effect needed for resonance

- π^0 production by neutrinos provides insight on π^0 –NC background to ν_e appearance
- π^0 production wants low Q^2 reduction – RPA effect for resonance production
- Not as strong for π^+ production

Phys. Rev. D 96, 072003 (2017)



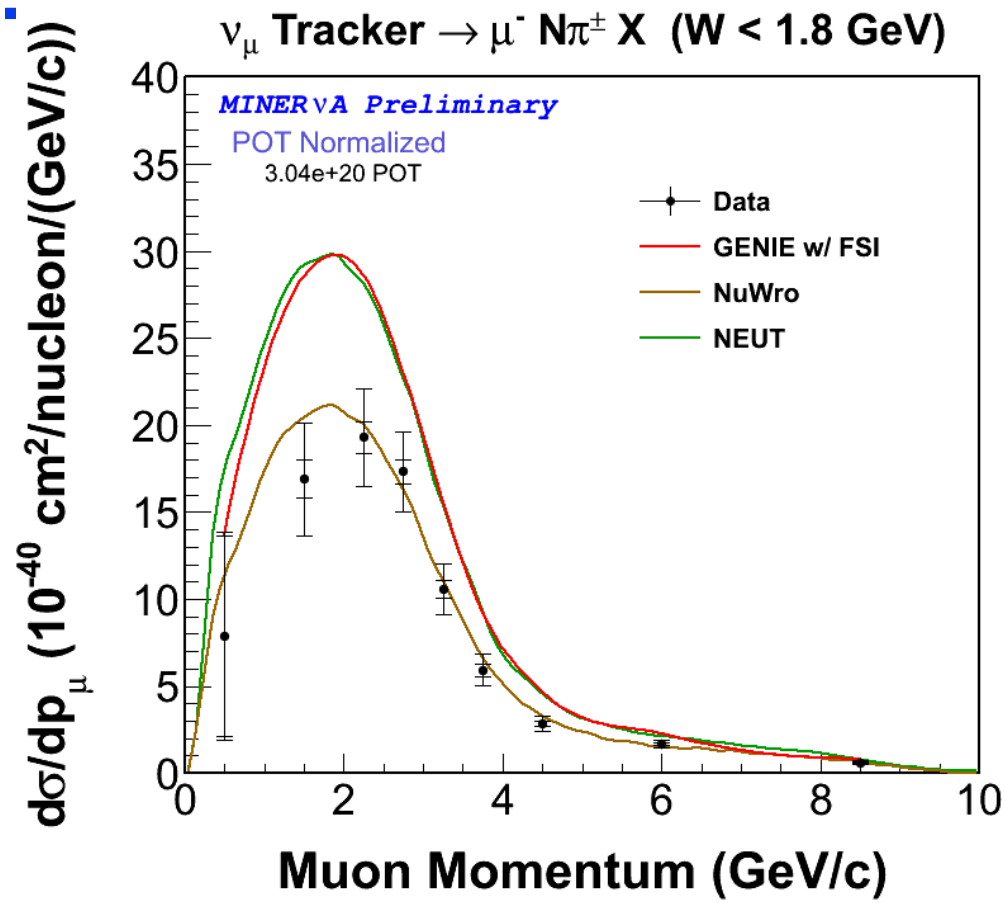
Phys. Rev. D 94, 052005 (2016)

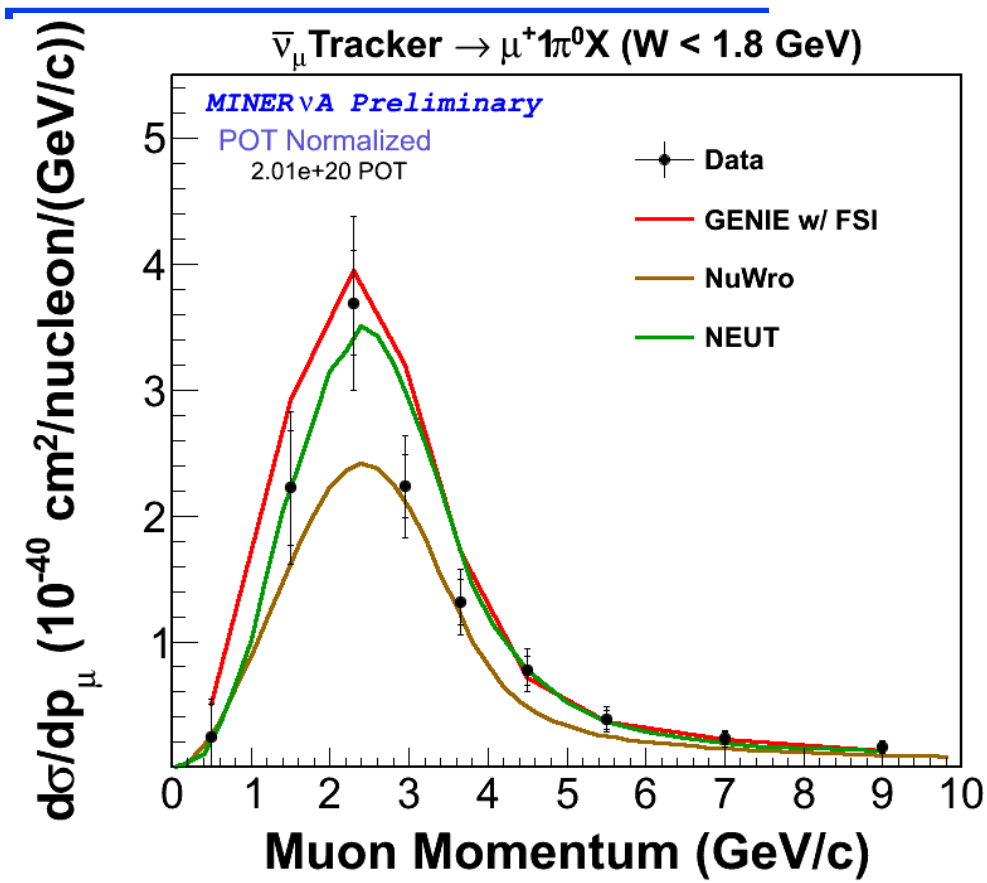


So let's start our examination of this region with Deep-Inelastic Scattering ($Q^2 > 1$ GeV^2 and $W > 2$ GeV)

- Why study Deep-Inelastic Scattering??
- Better understand the quark / parton structure of the free and bound nucleon.
- Test the predictions of (nuclear) Quantum Chromodynamics (QCD).
- How do we do study it?
  - Measure total and differential cross sections in x, Q^2 and W off various nuclei.
  - Extract the corresponding "nuclear structure functions" $F_i(x,Q^2)$ with i = 1,2 and 3.
  - Use the nuclear cross sections or nuclear F_i in global fits to determine **nuclear** parton distribution functions (nPDF).
  - Determine bound nucleon partonic nuclear effects by ratios of σ or F_i off a range of nuclei.
  - Determine quark hadronization by examining the make-up - multiplicities as function of $z \approx E_i / E_H$ and particle ID - of the hadron shower.
    - » Determine "hadron formation lengths" by comparing z distribution of various A.

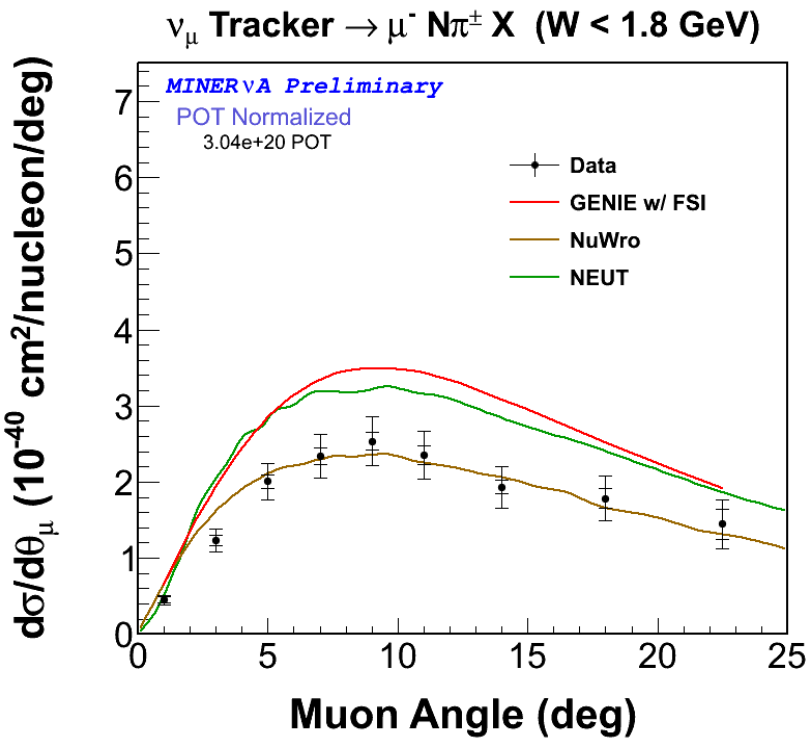
Start - Up into the multi-π zone (W < 1.8 GeV) from the lepton side: MINERνA cross section model comparisons for μ momentum

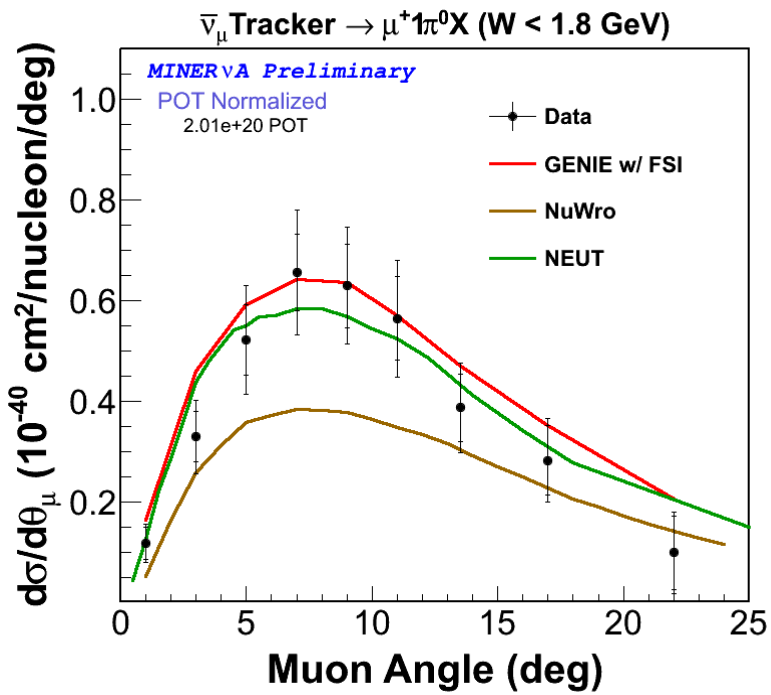




- In charged pion both GENIE and NEUT overestimate the cross section
- GENIE and NEUT predictions are similar and are higher than NuWro in both analyses

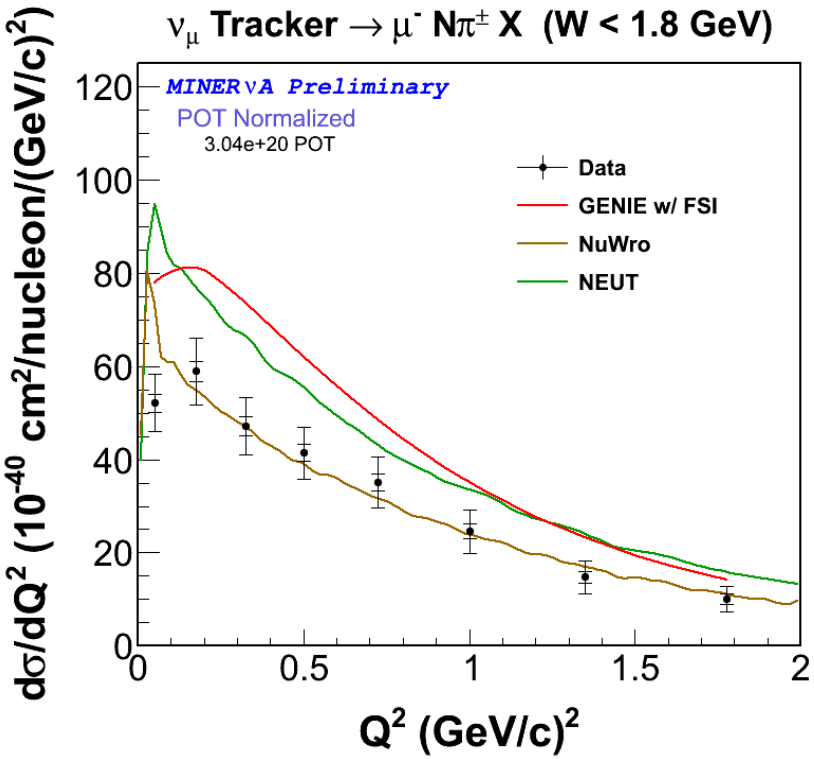
Up into the multi-π zone (W < 1.8 GeV) from the lepton side: MINERνA cross section model comparisons for μ angle

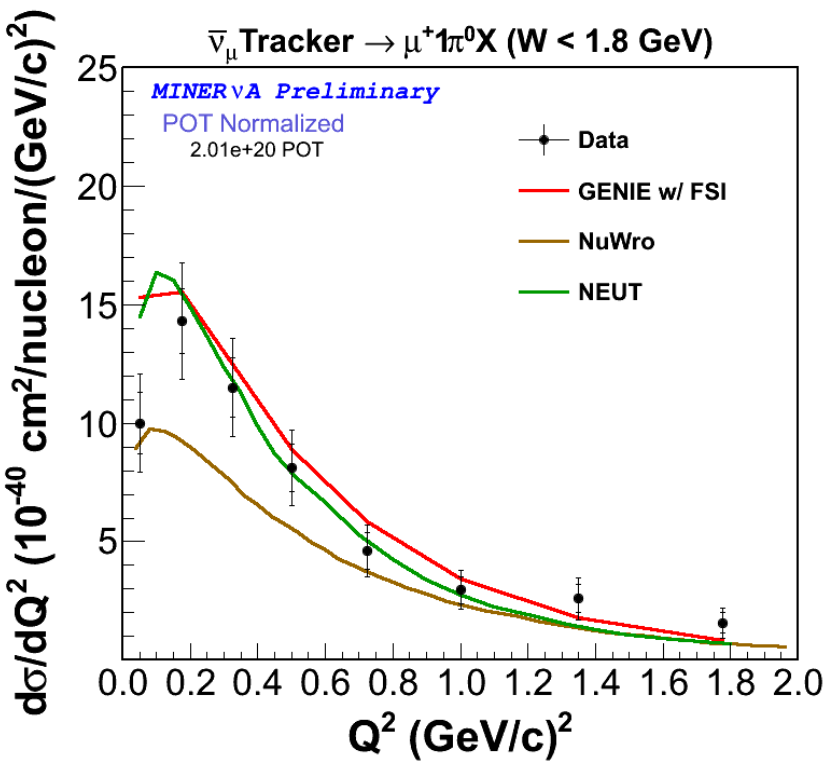




- The same normalization and shape behavior as with the μ mometum

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



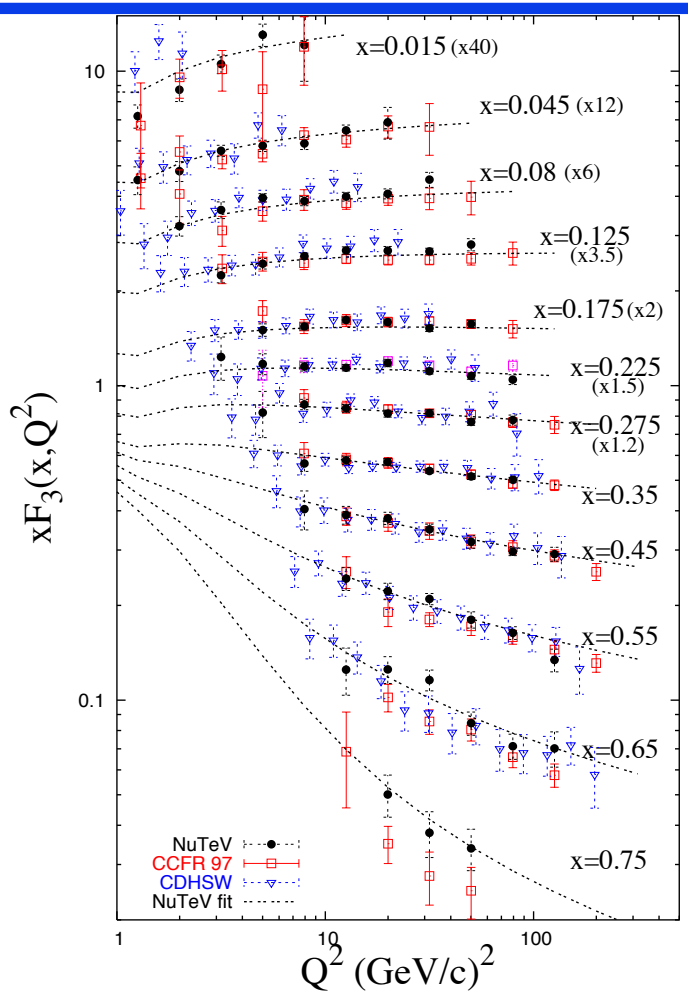


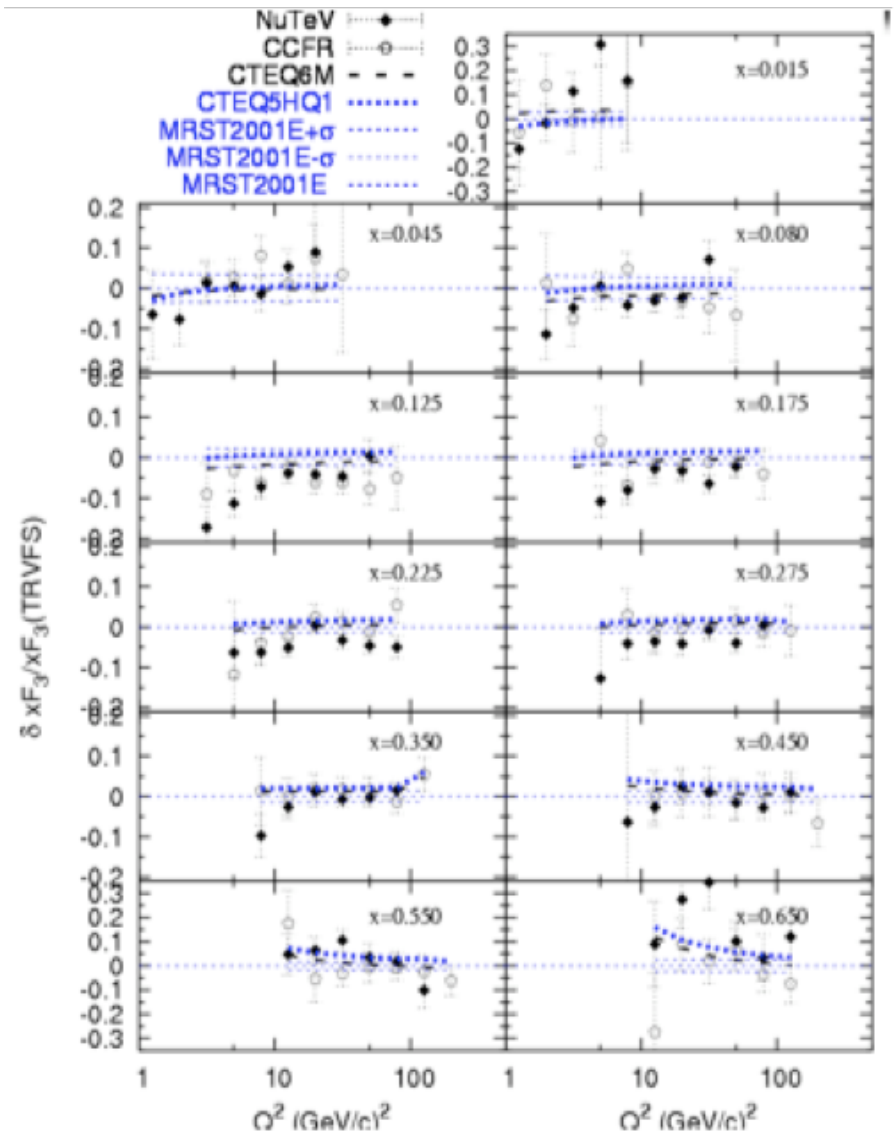
- In charged pion both GENIE and NEUT over estimate the cross section (as in the muon variables)
- In the shape analysis, GENIE agrees well with data except in lowest Q^2 bin of the neutral pions.
- In lowest Q^2 bin of the charged pions, coherent production in NuWro & NEUT

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!**

NuTeV Structure Function xF_3 Measurement on Fe





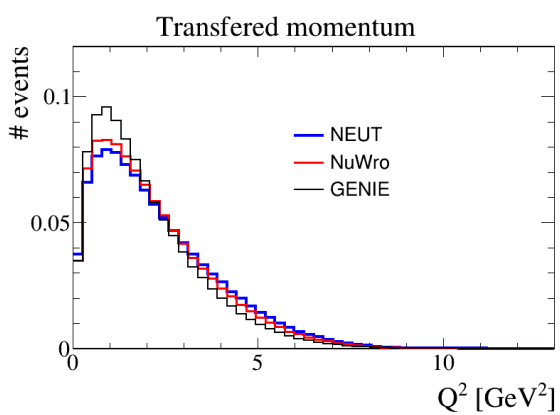
- At *x>0.5* NuTeV is systematically above CCFR
- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

The General Landscape - Comparison of Generators

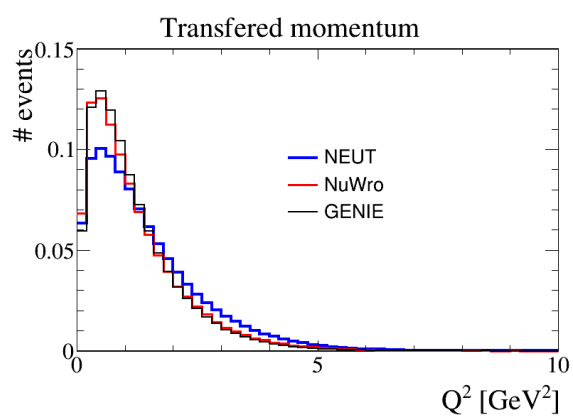
- Since ***over 45% of the DUNE events*** have W greater than 1.6 GeV), we need to consider what we do(little)/do-not(big) know about this region!
- This region includes a series of higher mass resonances that dwindle in number as W increases. For example, if we take W > 1.7 GeV to be "above" a majority of these resonances then the Q^2 distributions for a 6 GeV ν on Fe are predicted to look like this. Corrections to NEUT and GENIE yield improved agreement.

2016

Neutrino

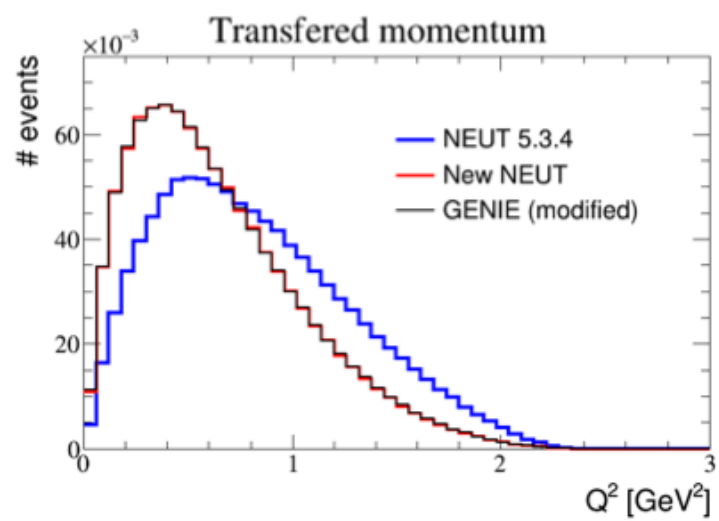


Anti-neutrino



C. Bronner- 2016

Neutrino - 2018



C. Bronner- 2018