Fermilab

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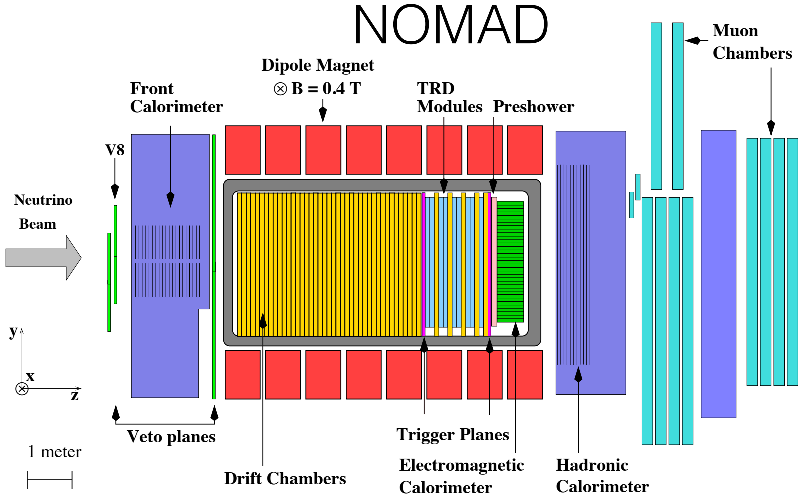
Overview of Neutrino Experiments

Minerba Betancourt
INT Workshop
29 September 2015

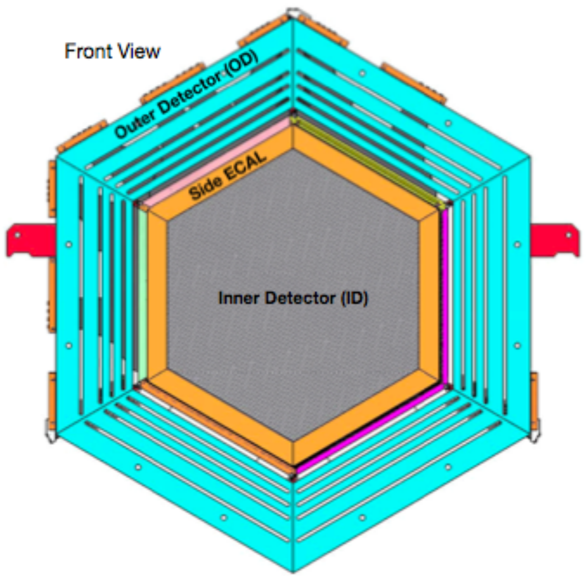
Neutrino Experiments

- Introduction
- Overview of cross section measurements
  - Quasi-elastic
  - Pion production
  - Charged current inclusive
  - Deep inelastic

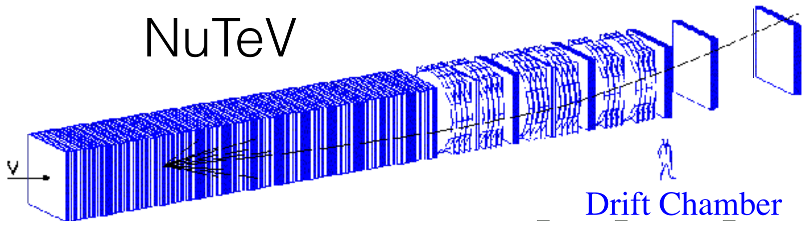
NOMAD



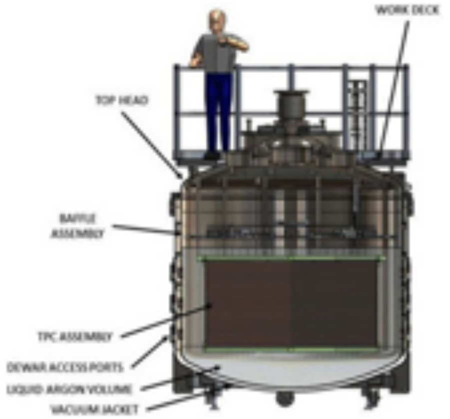
MINERvA



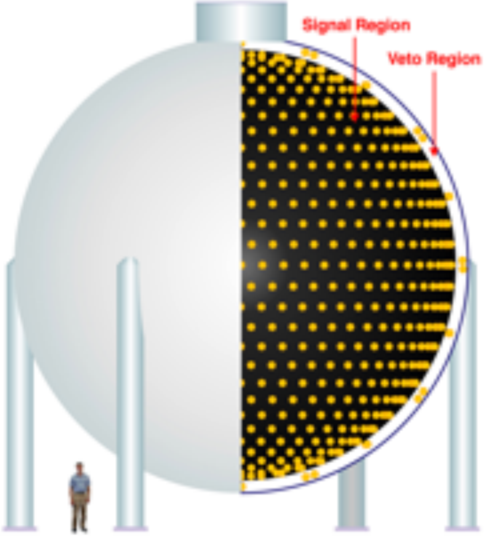
NuTeV



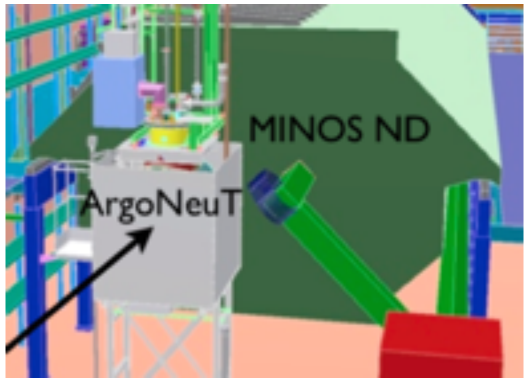
CAPTAIN



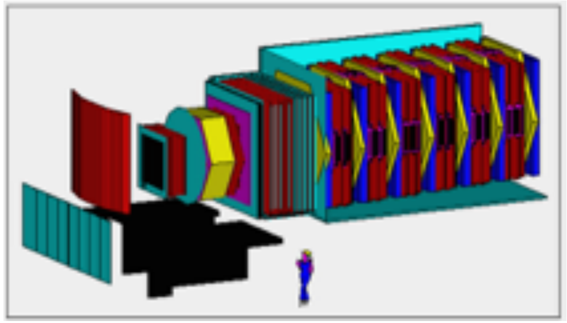
MiniBooNE



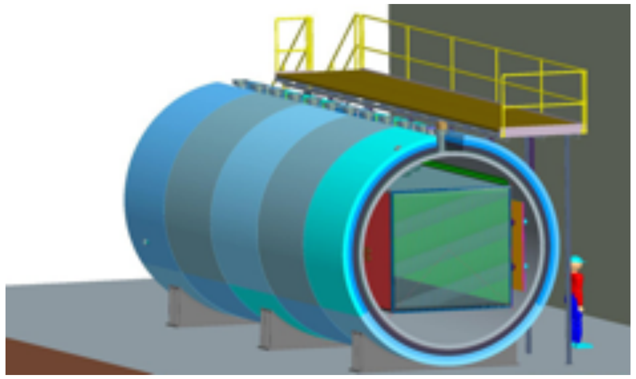
Argonout



CHORUS

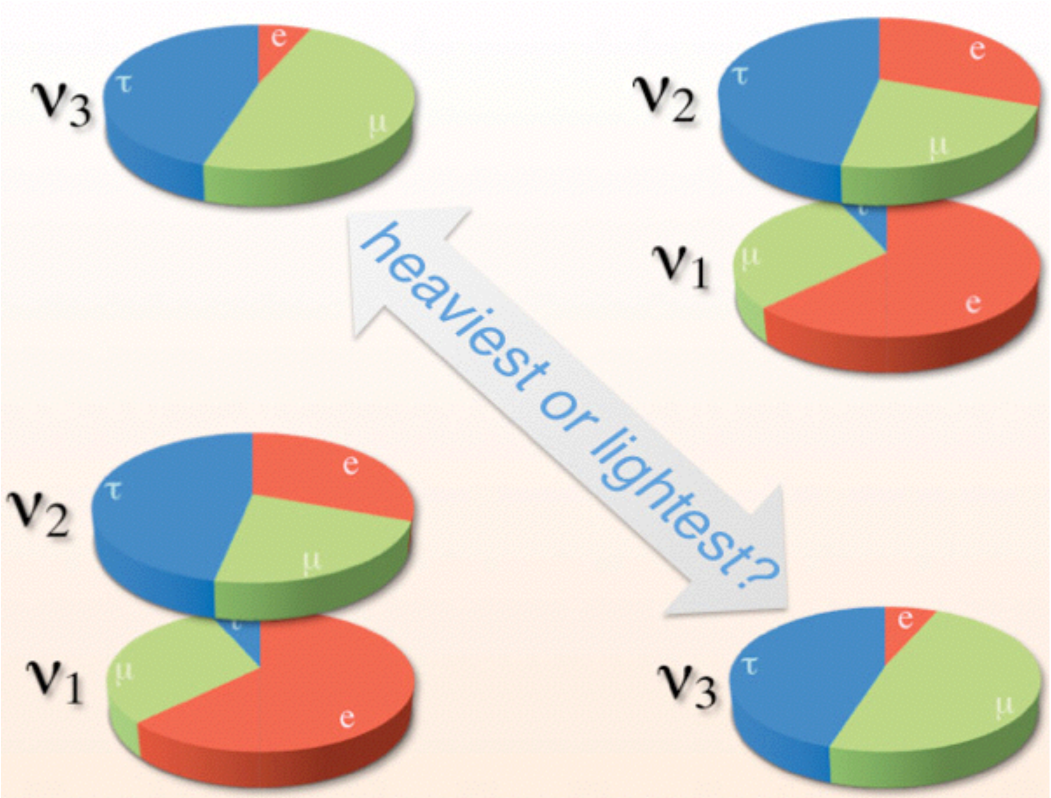


MicroBooNE



Introduction

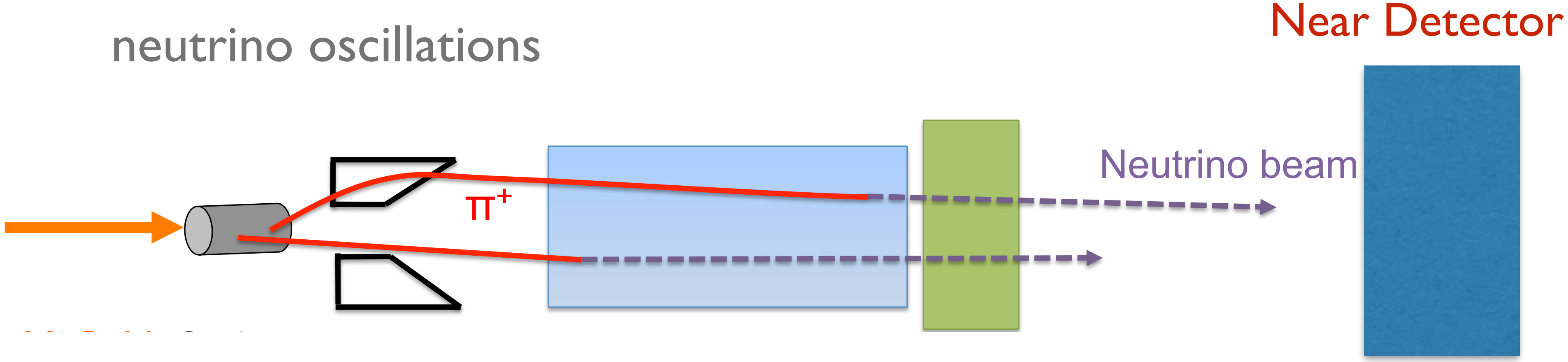
- From discovery of neutrino oscillation to an era of precision measurements

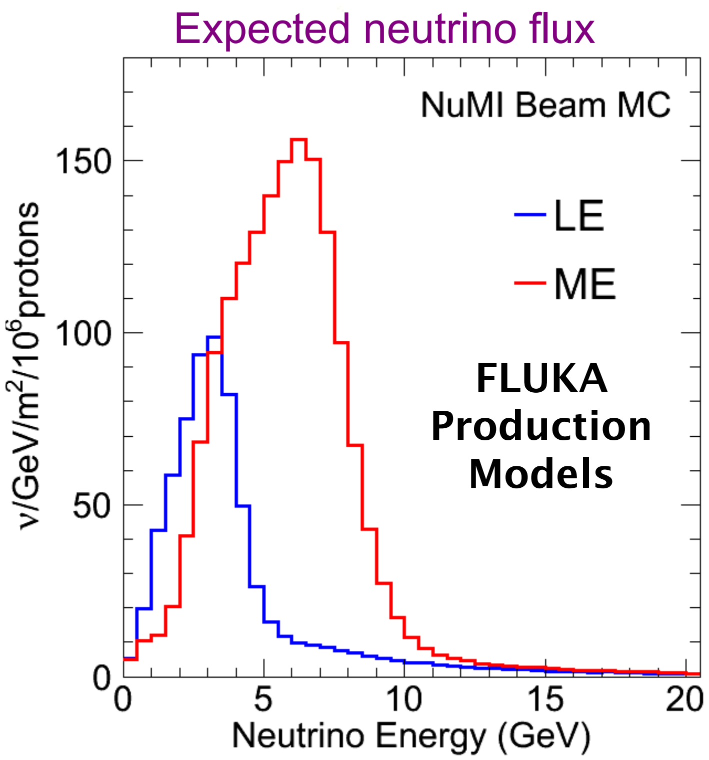


- Remaining questions: CP violation, mass ordering, anomalies: sterile neutrinos?
- To answer all of these questions we need to understand neutrino nucleus interaction physics
- Neither the cross sections nor nuclear effects for neutrino interactions in the few GeV region are well know
- A reliable model of neutrino interactions on heavy nuclei at low energies is essential for precise neutrino oscillations experiment

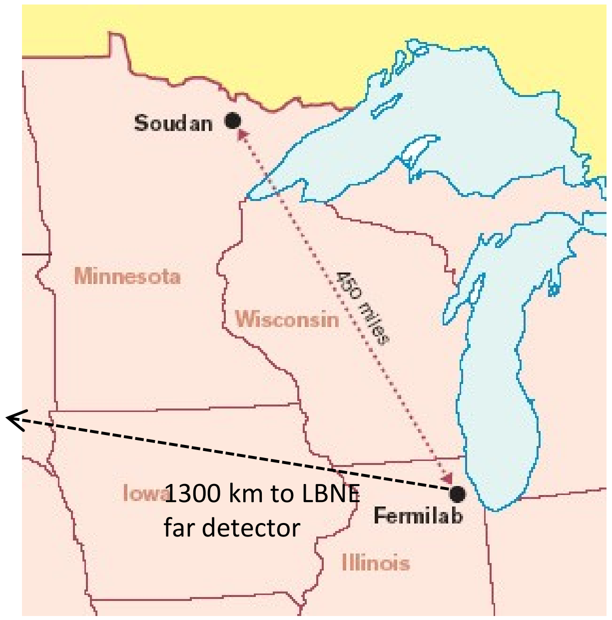
Neutrino Beam

- A beam of protons interact with a target and produce pions and kaons
- We use magnetic horns to focus the charged particles. These charge particles decay and produce the neutrino beam
- Long baseline experiments use near and far detectors to study neutrino oscillations





- To get sufficient statistic for oscillations we use powerful beams
- These powerful beams produce large statistics for near detector experiments to study neutrino scattering
- Different technologies are used to detect neutrinos



Original image: Symmetry Magazine, May 2005

Near Detector: Event Rates $\alpha \quad \phi \times \sigma \times \epsilon$

Far Detector: Event Rates $\alpha \quad \phi \times \sigma \times \epsilon \times P_{\nu_\mu \rightarrow \nu_e}$

Parameter Measurements

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

- From Reactor plus Solar

$$^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20}\times 10^{-5}\ \mathrm{eV}^2 \quad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

†PRD 83.052002(2011)

- From atmospheric and accelerator

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08}\times 10^{-3}\ \mathrm{eV}^2 \quad {}^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \mathrm{C.L.})$$

††PRL 106. 181801(2011)

- From neutrino reactor experiments, through the observation of electron antineutrino disappearance, θ_{13} is now best known mixing angle

	$sin^2 2\theta_{13}$
DoubleChooz:	0.090 ± 0.030
Daya Bay:	0.084 ± 0.005
††† RENO:	0.088 ± 0.011

†††
arXiv:1406.7763
Phys.Rev.Lett 115 (2015)11,111802
Phys.Rev. Lett 108 (2012)191802

- From accelerator experiments looking for either mass hierarchy or CP violation

†V T2K: Observed electron neutrino appearance signal at 7.3 σ

V NOvA: Observed electron neutrino appearance signal at 3.3 σ for primary selector and 5.5 σ for secondary selector

Favor $\pi < \delta_{CP} < 2\pi$ normal mass ordering

†VPhys. Rev. D 91, 072010

Vhttp://theory.fnal.gov/jetp/talks/20150806_nova_docdb.pdf

Current Neutrino Program

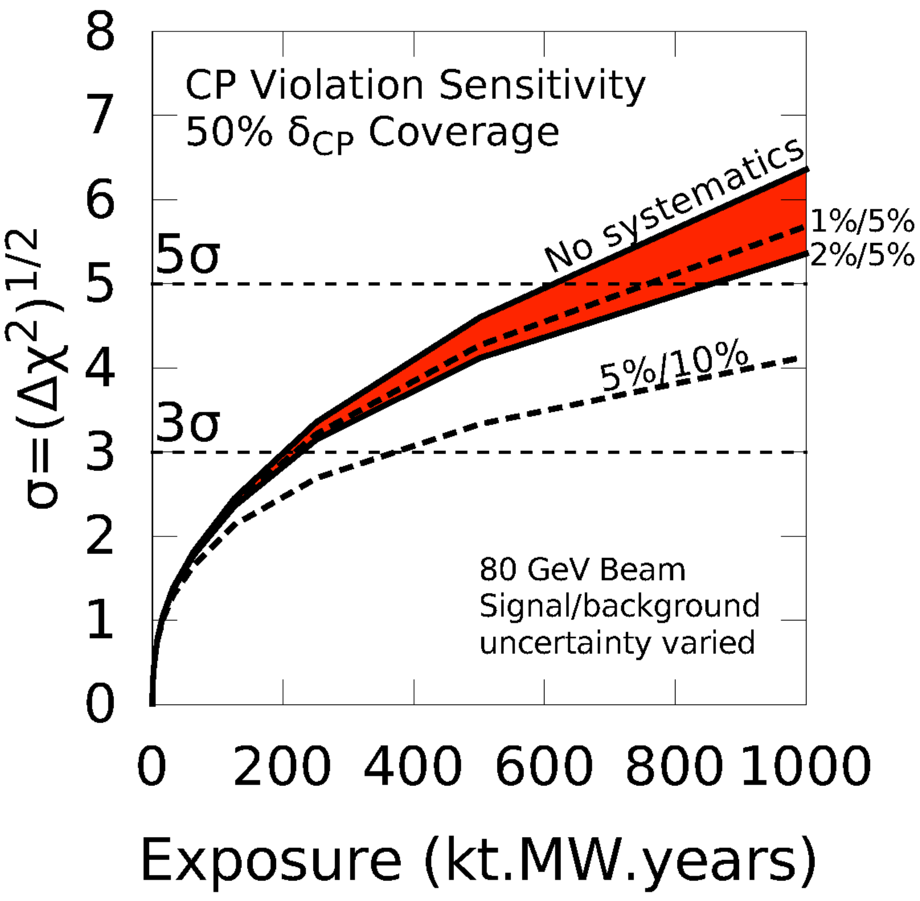
- Covering only neutrinos made with accelerator at low GeV
- We have many neutrino experiments around the world
- Fermilab is planning a big program for neutrinos. The neutrino program contains a short baseline, long baseline and neutrino scattering experiments

- **The short baseline program** will study neutrino anomalies and sterile neutrinos
  - Several experiments: MiniBooNE, LAriaT, ICARUS, SBND, MicroBooNE
- **The long baseline program** is making precision measurements, muon neutrino appearance, muon neutrino disappearance, search for CPV and mass hierarchy
  - Oscillation experiments MINOS, NOvA, T2K, DUNE and HyperK
- **Scattering experiment**: MINERvA, MiniBooNE, ArgoNeuT, T2K, NOvA, MicroBooNE

DUNE Experiment

- DUNE will use a wideband beam peaked at 2.5-3.0 GeV
- Far detector will be a LArTPC detector and current design for near detector is a fine grained tracker with low density
- We need to understand the neutrino interactions well, especially if near and far detectors are made with different technologies
- Science program covers CPV in the leptonic sector, mass hierarchy, precision oscillation physics for the 3-flavor paradigm, nucleon decay and supernova burst

- How different levels of systematic uncertainties impact the CP violation in DUNE:
  - Oscillation experiments see differences between near detector data and MC simulation well above systematic errors assumed here
  - Systematic uncertainties are important for the CP violation measurement

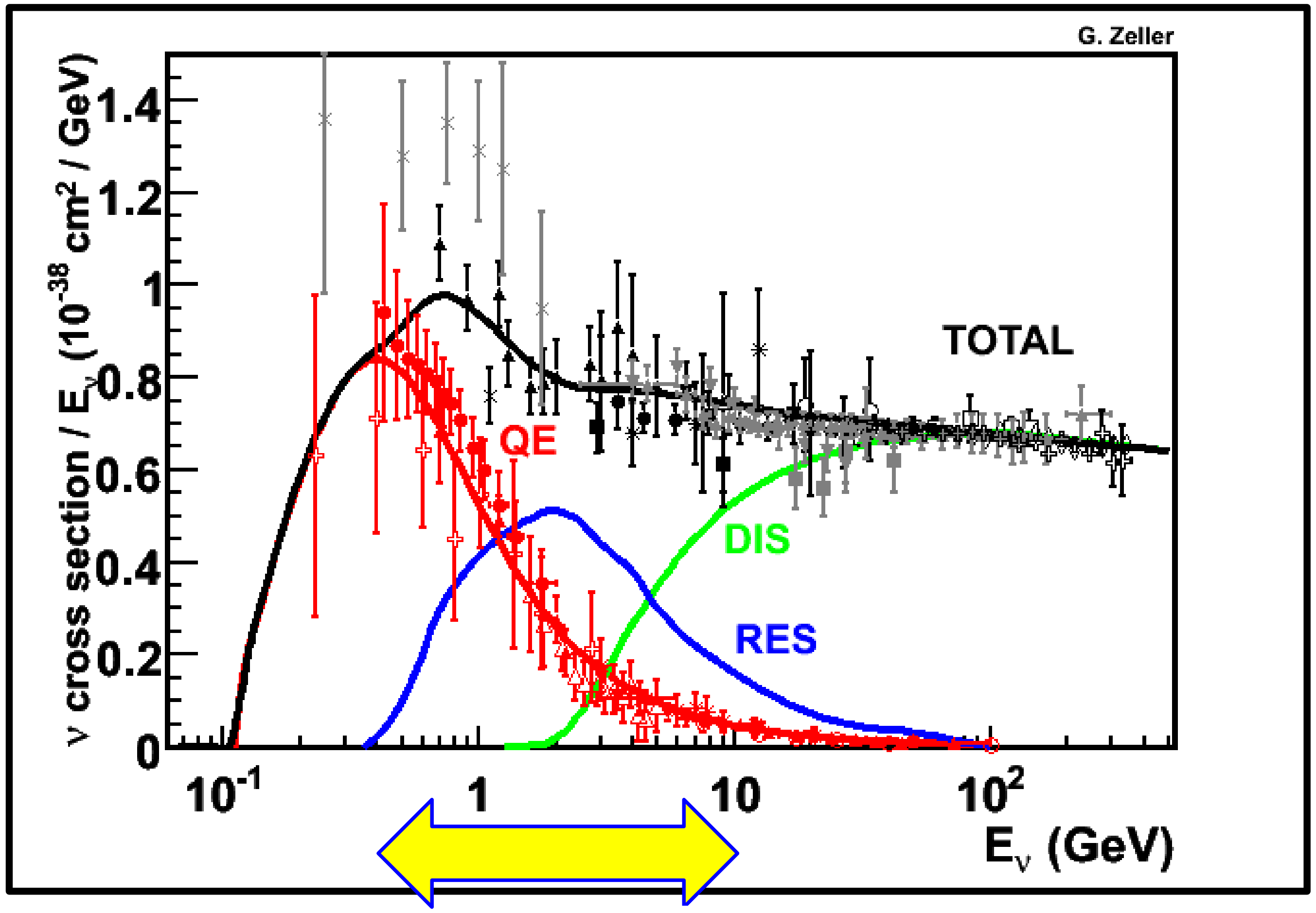


Scientific Opportunities with the Long-Baseline Neutrino Experiment

Neutrino Cross Section up to DIS

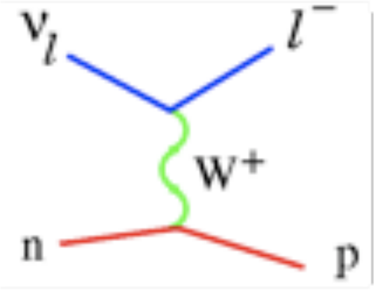
- Measurements for neutrino charged current interaction, colors correspond the classification from the simulation

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



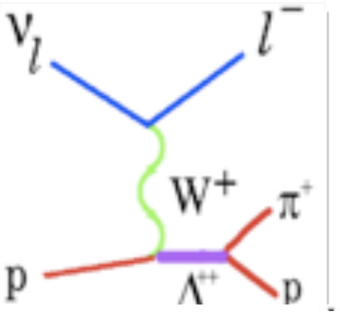
T2K **DUNE**

NOνA



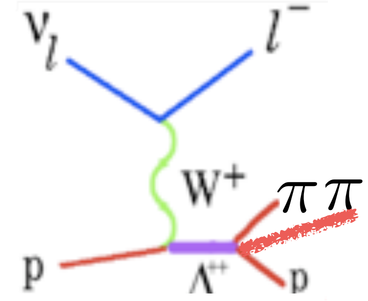
CC Quasi-Elastic

nucleon changes, but doesn't break up

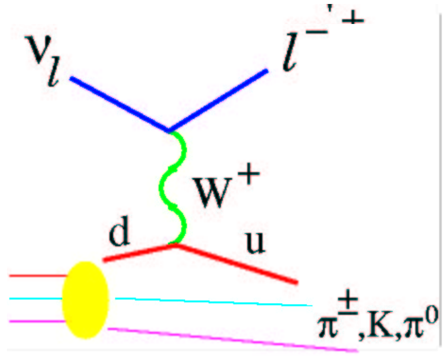


CC Resonance

nucleon excites to resonance state



Transition region is not included in the resonance region (1 pion to muti pion until the deep inelastic)



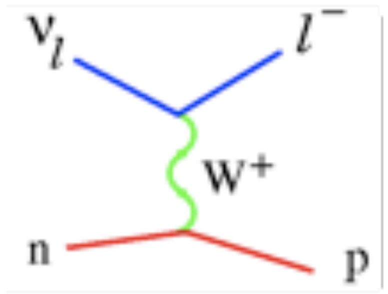
CC Deep Inelastic

nucleon breaks up

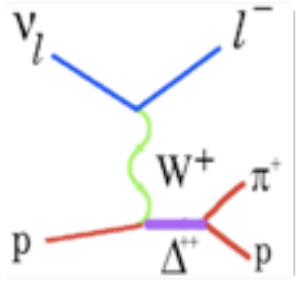
Neutrino Interactions

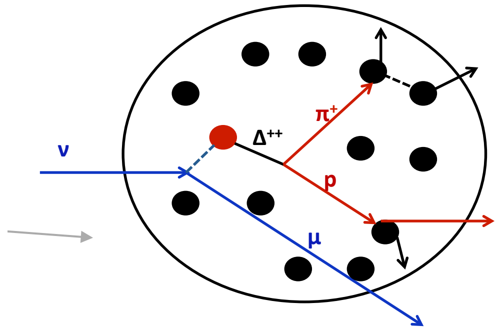
- Charged current processes are signal channels for oscillation experiments
- Due to nuclear effects combined with cross section, the channels and neutrino energy measured in detectors are not necessarily the same as produced in the initial interaction

CC Quasi-Elastic



CC Resonance

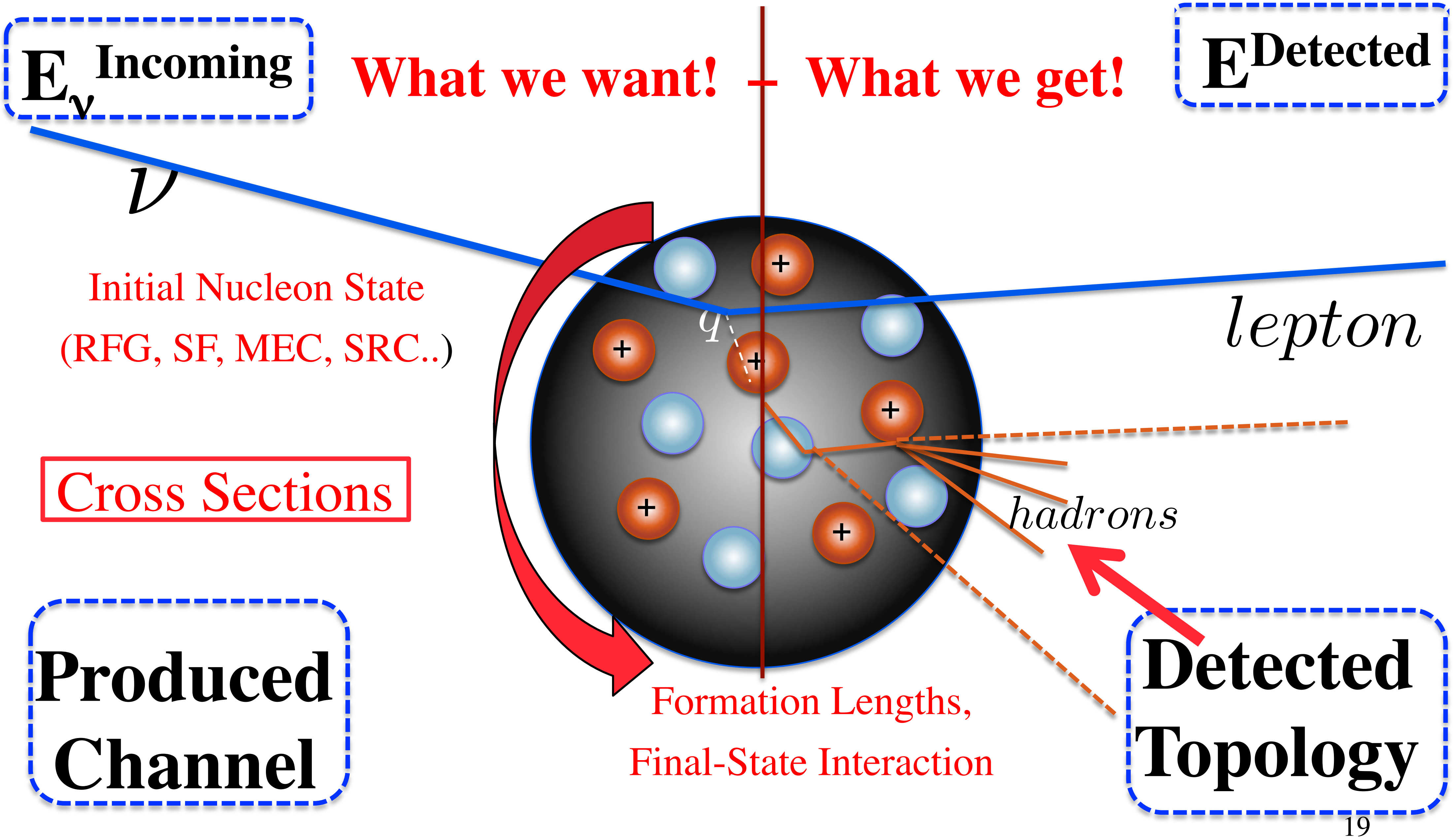




Pion Absorption: Due to final state interactions particles can interact with nucleons before exiting the nucleus

- A nuclear model is needed to relate detected channel and energy with initially produced channel and energy
- A pattern of neutrino oscillation is analyzed based on distributions of detected particles and it is crucial to have a reliable MC generator to read this pattern correctly
- Recent experimental data is not well described by current models
- Understanding the neutrino interactions with nuclei is vital for precision oscillation measurements

Neutrino Nucleus Scattering



E_ν^{Incoming}

What we want!

What we get!

E^{Detected}

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

Cross Sections

Produced Channel

Formation Lengths,
Final-State Interaction

Detected Topology

Jorge Morfin, INFO 2015

Neutrino Nucleus Scattering

- The events we observe on our detectors are convolutions of

$$Y_{c-like}(E_d) \quad \alpha \quad \phi_\nu(E' \geq E_d) \otimes \sigma(E' \geq E_d) \otimes Nuc(E' \geq E_d)$$

- 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 error on measurements

- Current Generator 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
- GIBUU Nuclear Transport Model

Charged Current Quasi-elastic Scattering

Charged Current Quasi-Elastic Scattering (CCQE)

- Quasi-elastic is one of the simplest channel in neutrino scattering
- We use a free nucleon CCQE formalism:

$$\frac{d\sigma}{dQ^2_{QE}} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\{A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\}$$

- where A, B and C depend on the form factor F1, F2 and the axial form factor F_A
- Most of the form factors are known, except the axial form factor F_A. This is parameterized as a dipole

$$F_A(Q^2) = \frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}$$

A goal of neutrino experiments is to measure F_A

- Recent effort:

More details at talks from Martha Constantinou and Aaron Meyer

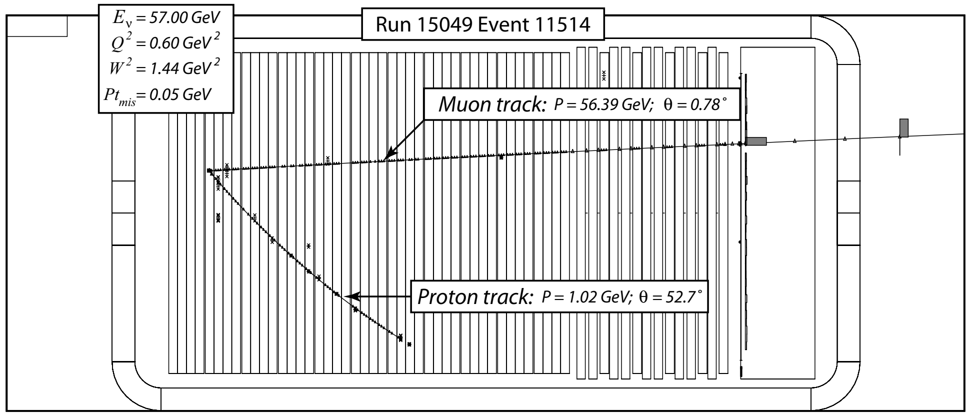
  - A new model-independent description of the axial mass form factor called Z-Expansion from Bhubanjyoti B., Richard H. and Gil P., Phys. Rev. D 84 073006
  - New effort to to calculate the shape of F_A in lattice QCD, "The Nucleon Axial-Vector Form Factor at the Physical Point with the HISQ Ensembles", A. Bazavov et al. Fermilab Lattice and MILC collaborations
- We are looking forward to the contribution with lattice QCD

Quasi-Elastic Scattering

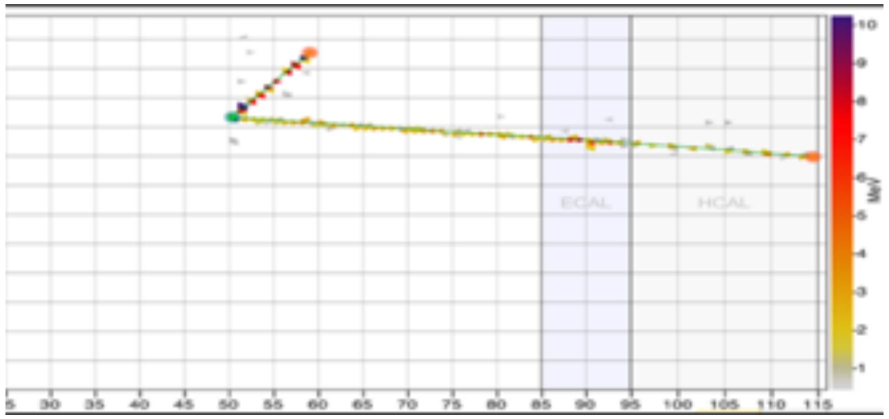
- Quasi-elastic gives the largest contributions for the signal in many oscillation experiment
- Early neutrino scattering experiments used bubble chambers filled with D2 with excellent quasi-elastic purity 97-99%
- Modern experiments use different targets, such as carbon, iron, oxygen, liquid argon.. etc
- We have more statistics, but with the heavy targets we have more nuclear effects
- In addition quasi-elastic purities are much lower, below 80%
- The QE selection varies from experiment to experiment, some experiments uses only the muon and other use the proton and muon

$$Q^2 = 2E_\nu(E_\mu - p_\mu cos\theta_\mu) - m_\mu^2$$

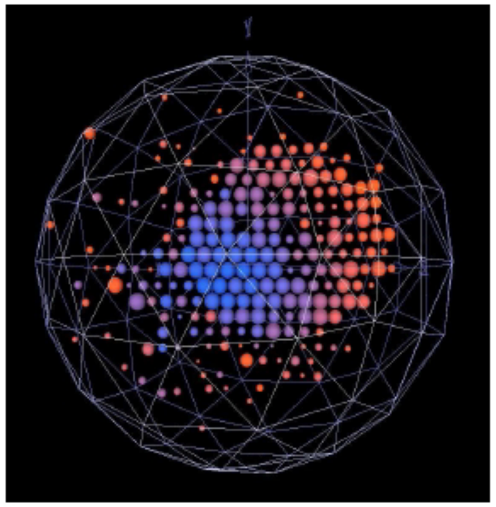
NOMAD



MINERvA



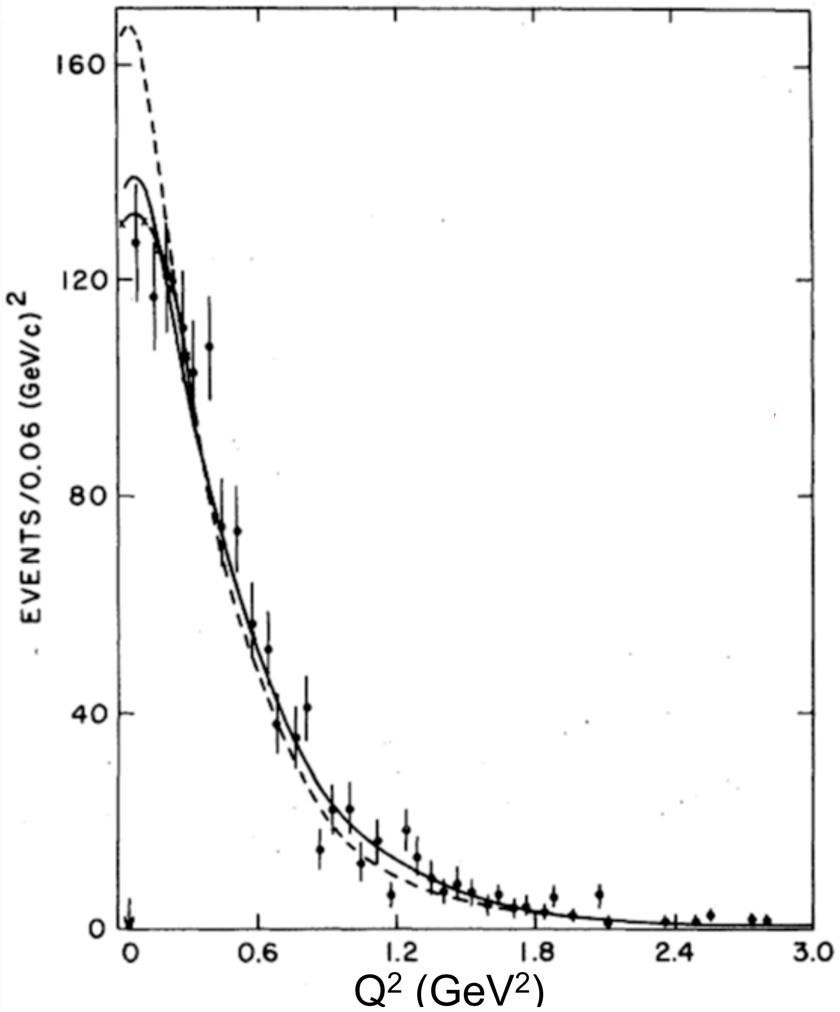
MiniBooNE



Quasi-Elastic Scattering Measurement from Deuterium Experiments

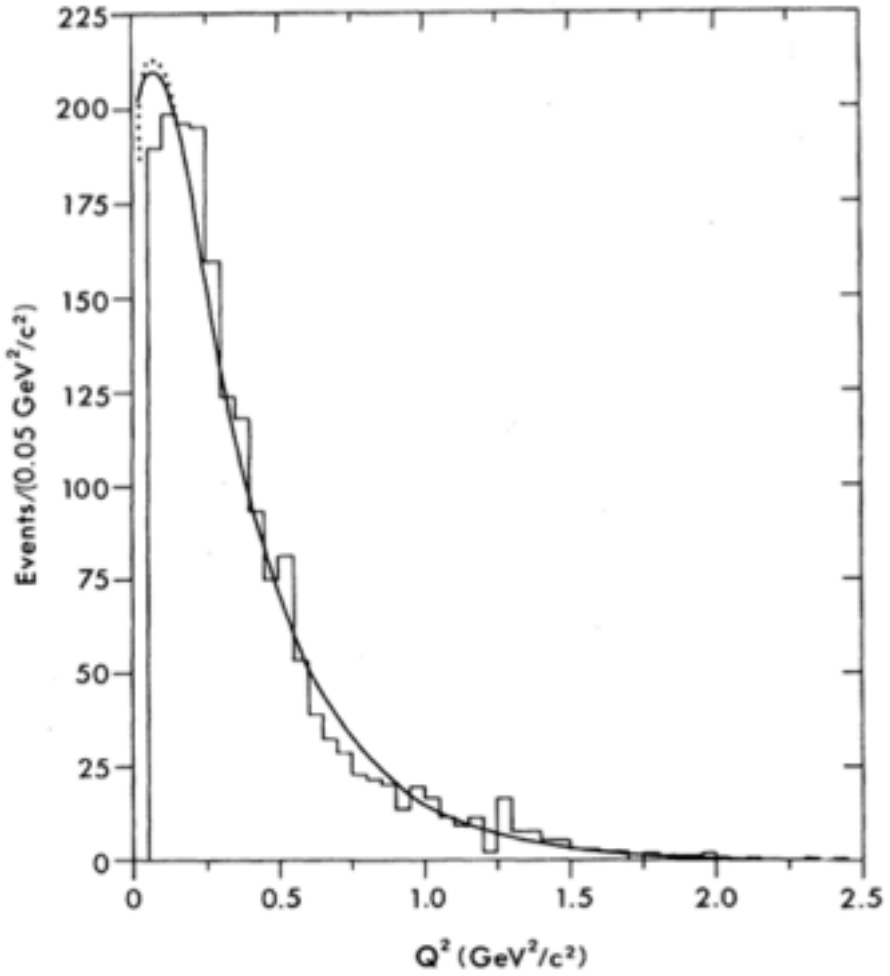
- These experiments measured the axial mass M_A, pretty good agreement between the experiments

$$M_A = 1.07 \pm 0.06 GeV$$



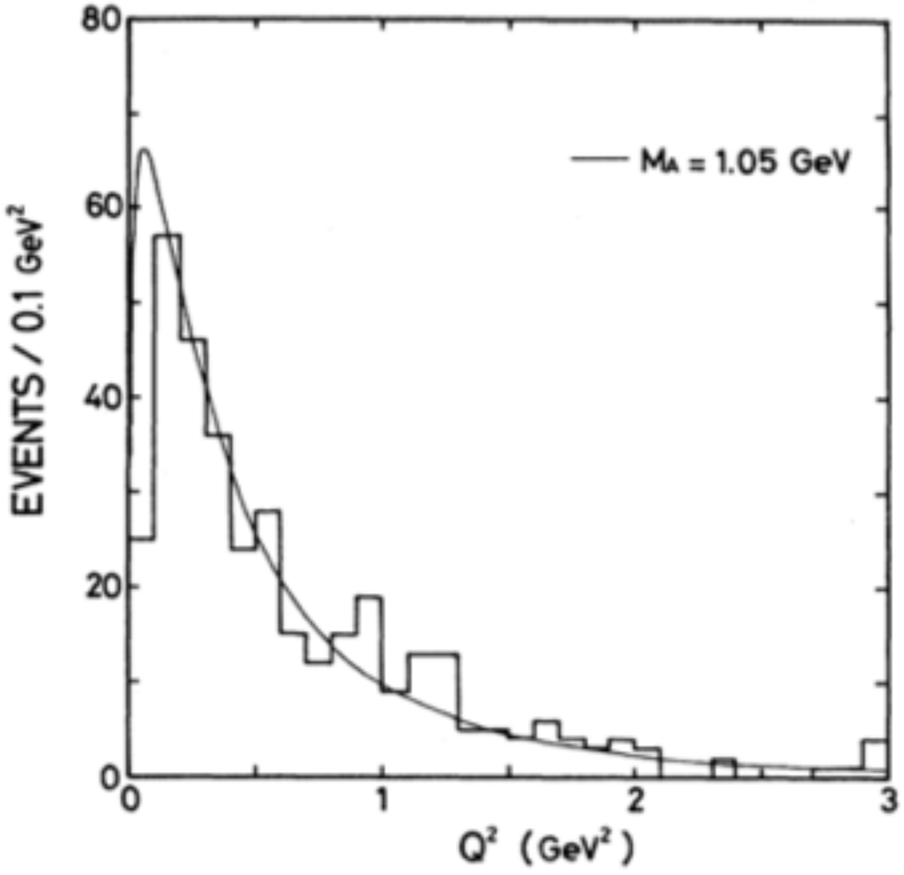
Baker, PRD 23, 2499 (1981)

$$M_A = 1.00 \pm 0.05 GeV$$



Miller, PRD 26, 537 (1982)

$$M_A = 1.05 \pm 0.16 GeV$$



Kitagaki, PRD 28, 436 (1983)

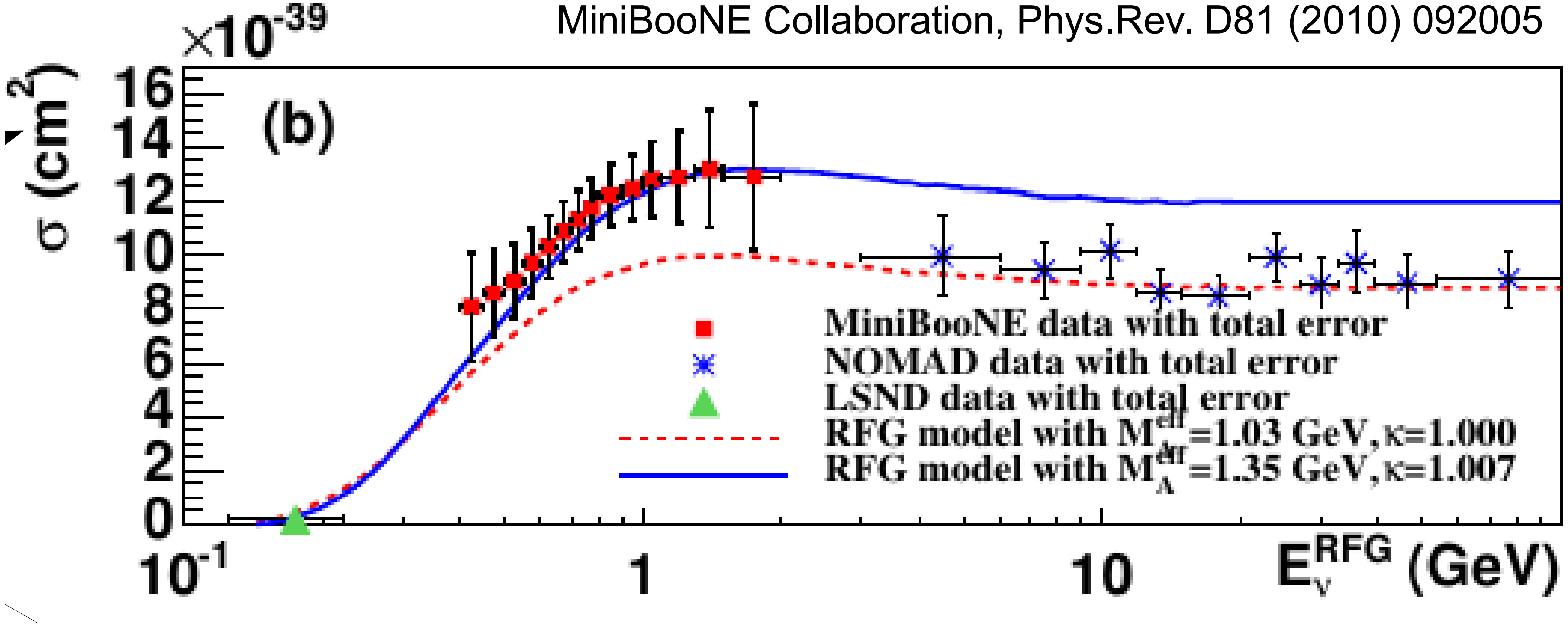
$$\boxed{M_A = (1.026 \pm 0.021)\ GeV/c^2}$$

Quasi-Elastic Scattering (CCQE)

- Some examples of modern experiments:
  - NOMAD experiment uses carbon as a target and a tracker detector with high energy experiment <E>=24GeV, both 1 and 2 track were measured (purity 50%).
    Signal definition: quasi-elastic events
  - MiniBooNE uses carbon as a target and a Cherenkov detector with low energy <E>=0.8GeV, analysis used ν_μ CC with no pions (purity 77%).
    Signal definition: events with no pions

Data is compared against a prediction based on Relativistic Fermi Gas Model

MiniBooNE Collaboration, Phys.Rev. D81 (2010) 092005



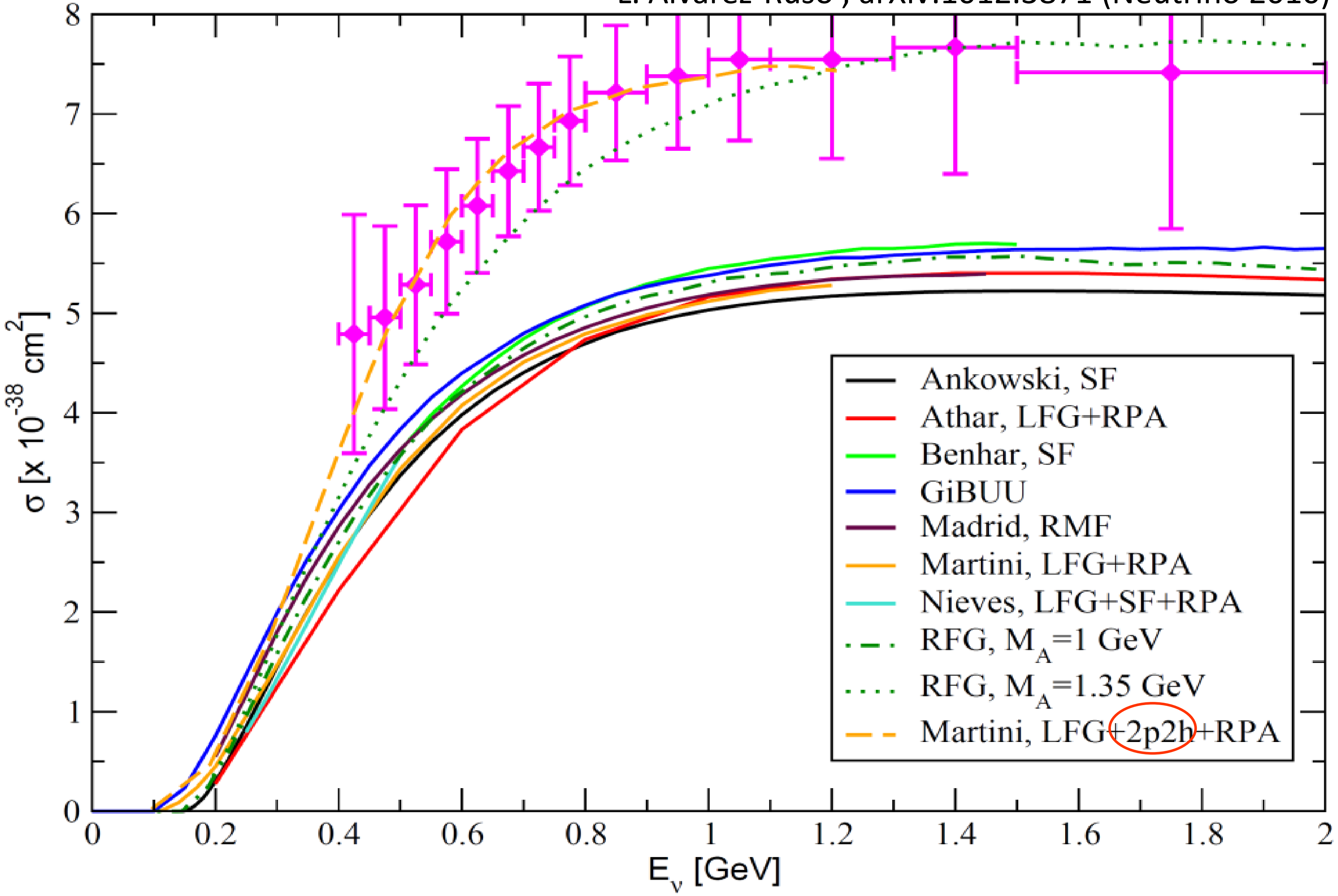
MiniBoonNE data fits better to an Axial Mass 1.35 GeV while NOMAD fits to an Axial Mass of 1 GeV

puzzle?

Quasi-Elastic Scattering Models

- Different models for CCQE

L. Alvarez-Ruso , arXiv:1012.3871 (Neutrino 2010)



SF: Spectral Function

LFG: Local Fermi Gas

RPA: Random Phase Approximation

RMF: Relativistic Mean Field

GiBUU: Transport Equation

Comparison of models and Monte Carlo:
Boyd, Dytman, Hernandez, Sobczyk, Tacik ,
AIP Conf.Proc. 1189 (2009) 60-73

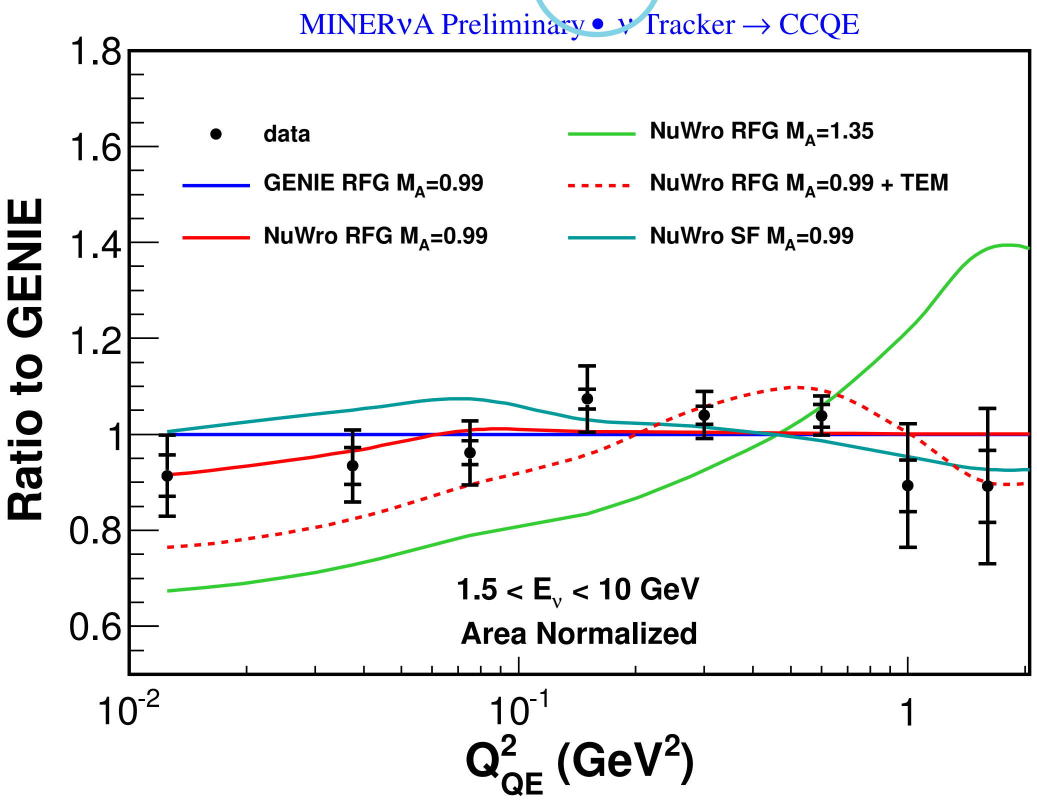
- Inclusion of the multinucleon emission channel (np-nh) gives better agreement with MiniBooNE data without increasing the axial mass
- Theorists have made a lot effort these past years to improve the models

Charged Current Quasi-Elastic Scattering from MINERvA

- MINERvA uses a tracking detector made of carbon, results will show the data collected with an energy <E>=3.5GeV

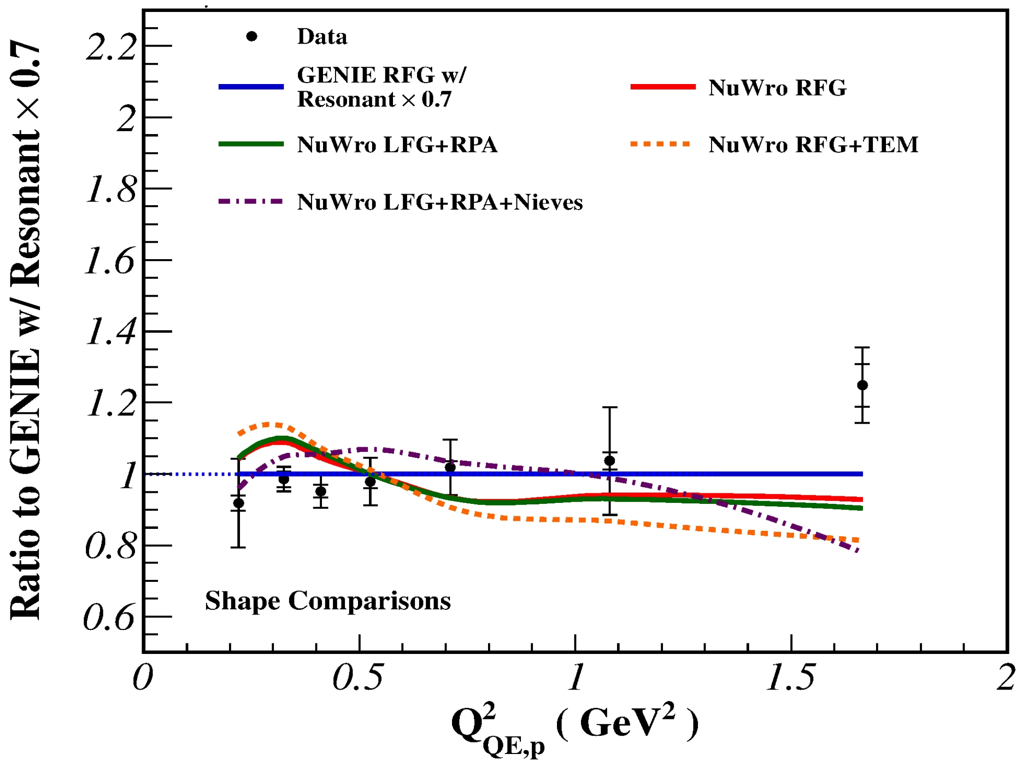
- MINERvA uses the lepton kinematics and the hadronic part of the interaction to measure the CCQE single differential cross section and discriminates between nuclear models

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



Phys. Rev. Lett. 111, 022501 (2013)

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



Phys Rev D. 91, 071301 (2015)

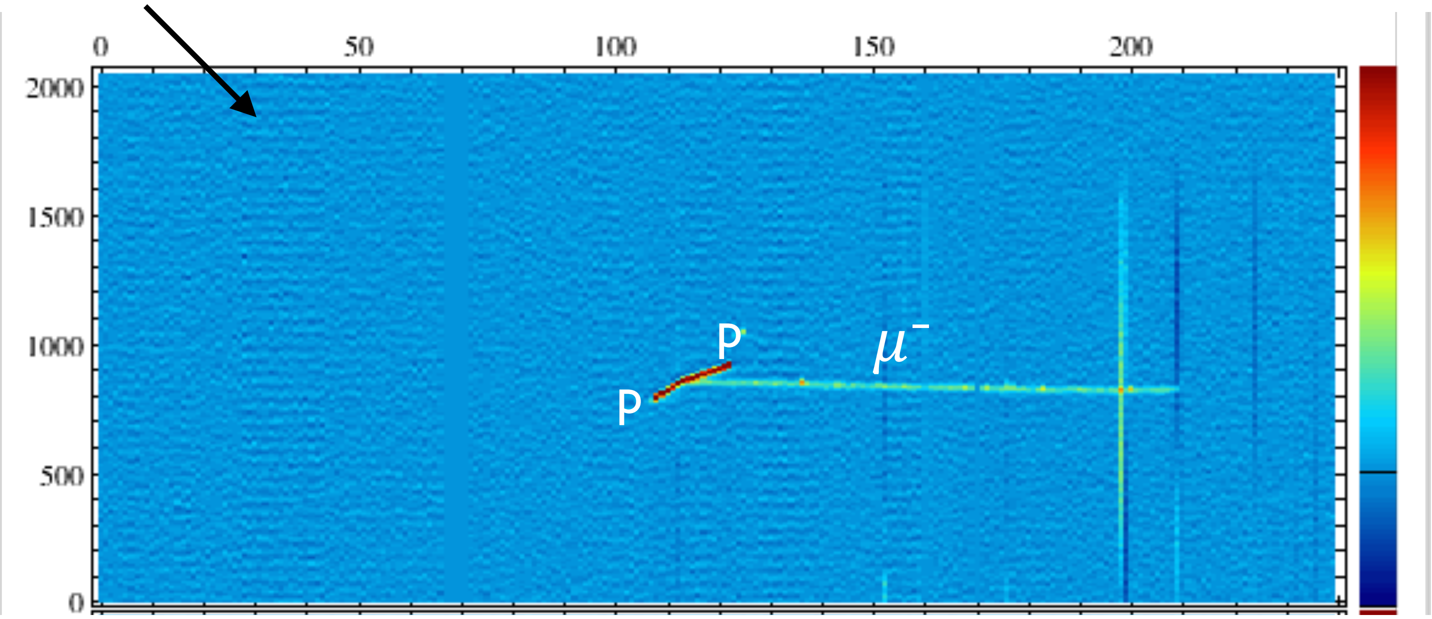
- Analyses using the muon information use a quasi-elastic signal definition and the purity is 49% for neutrinos, while the analysis using the proton information uses cc quasi-elastic like and the purity is ~65%

- Data prefers a model with nucleon-nucleon correlations for the muon analyses

Data from LArTPC ArgoNeut

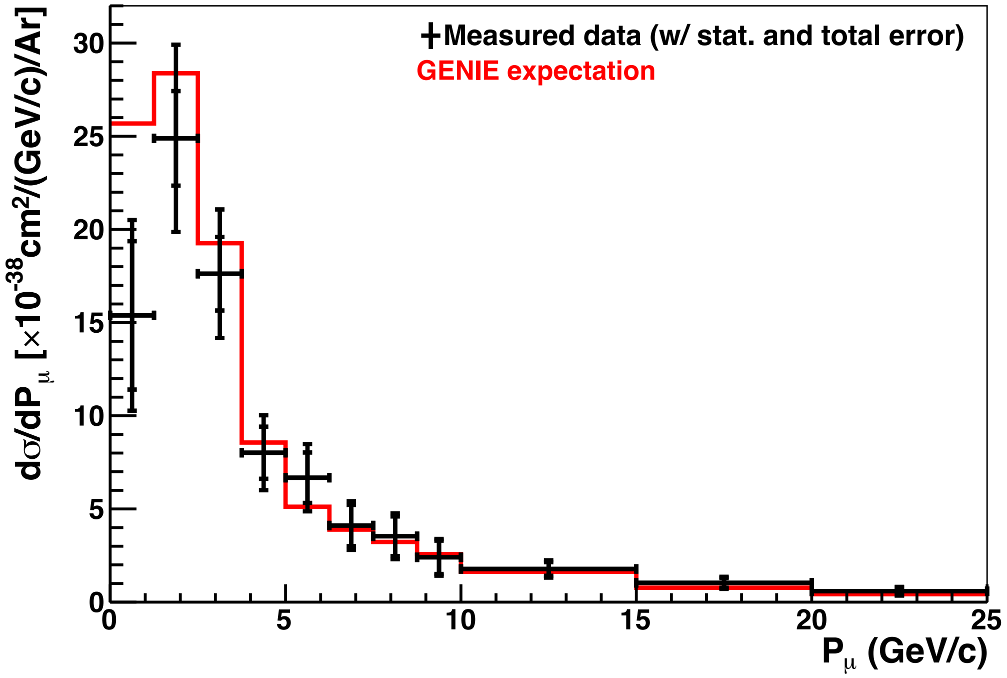
- First liquid argon experiment in a low (1-10 GeV) energy neutrino beam. Prototype experiment with 240 Kg of active volume
- Proton energy threshold 21 MeV kinetic energy
- Beautiful technology that allows to learn about features of neutrino interactions that have not been possible to explore with existing experiments
- Published inclusive muon neutrino charged current differential cross section as a function of momentum
- Studied a data sample of (muon+2p) and found 19 events with two proton
  - From which four events has back to back protons pairs

First time these events are observed



Phys. Rev. D 90,012008

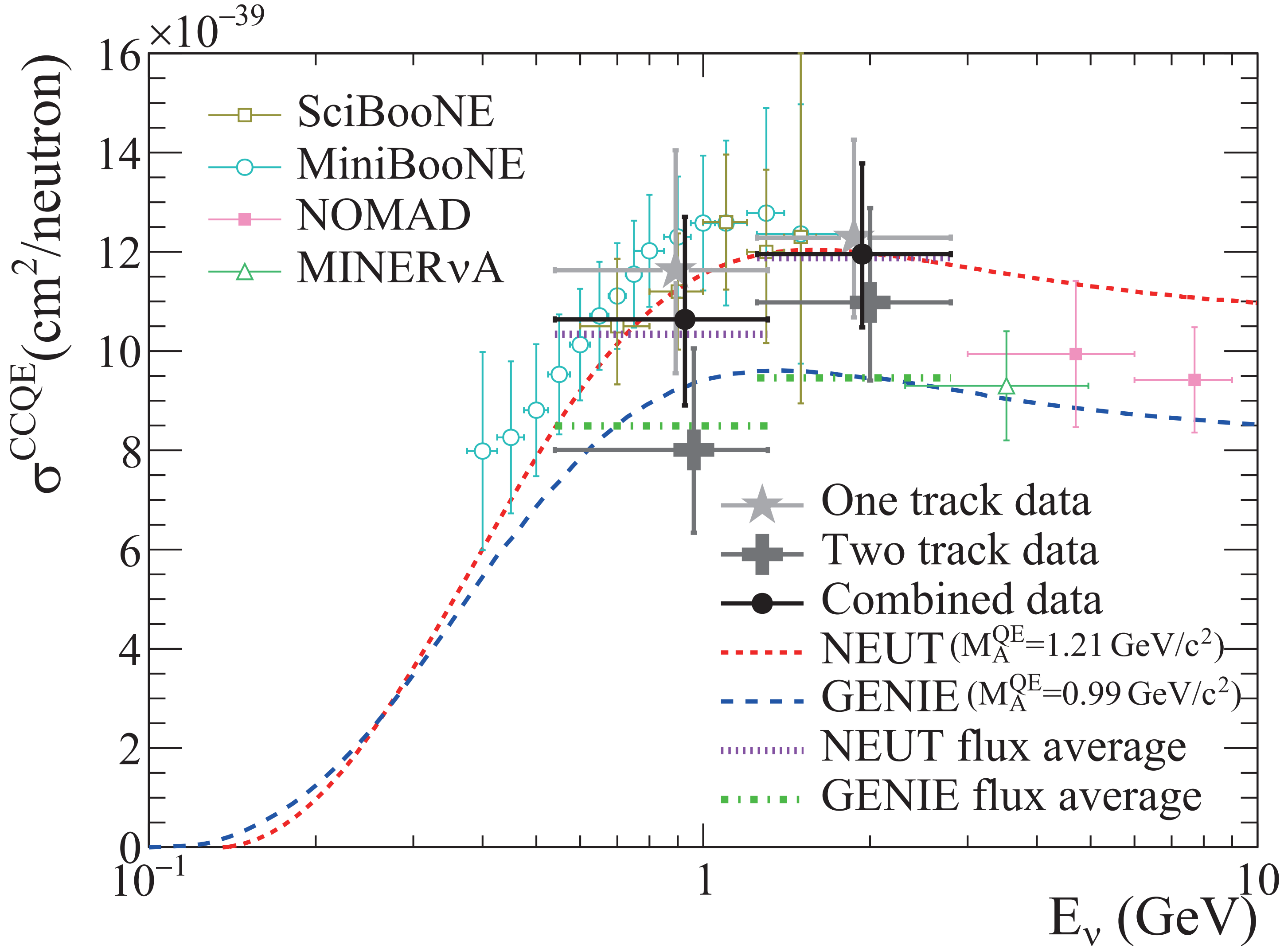
Inclusive muon neutrino charged current differential cross section



Phys. Rev. Lett. 108, 161802

Charged Current Quasi-Elastic Scattering from T2K

- T2K measured the CCQE with the INGRID detector. This detector uses a fully active tracking detector and located on-axis from the neutrino beam peak at 1.5 GeV
- Both one and two track events are measured, purity for one track events is 76% and purity for two track events is 85%



Phys. Rev. D 91,112002

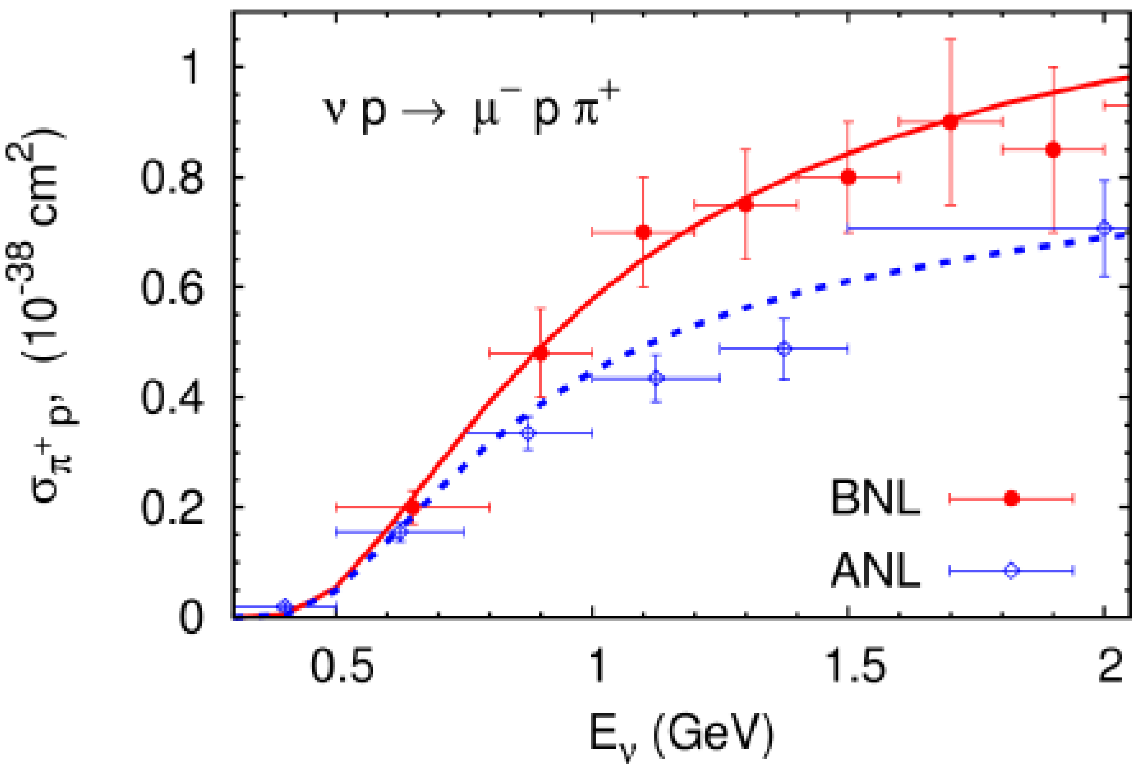
- Results agree with the predictions of neutrino interaction models

Pion Production

Charged Pion Production

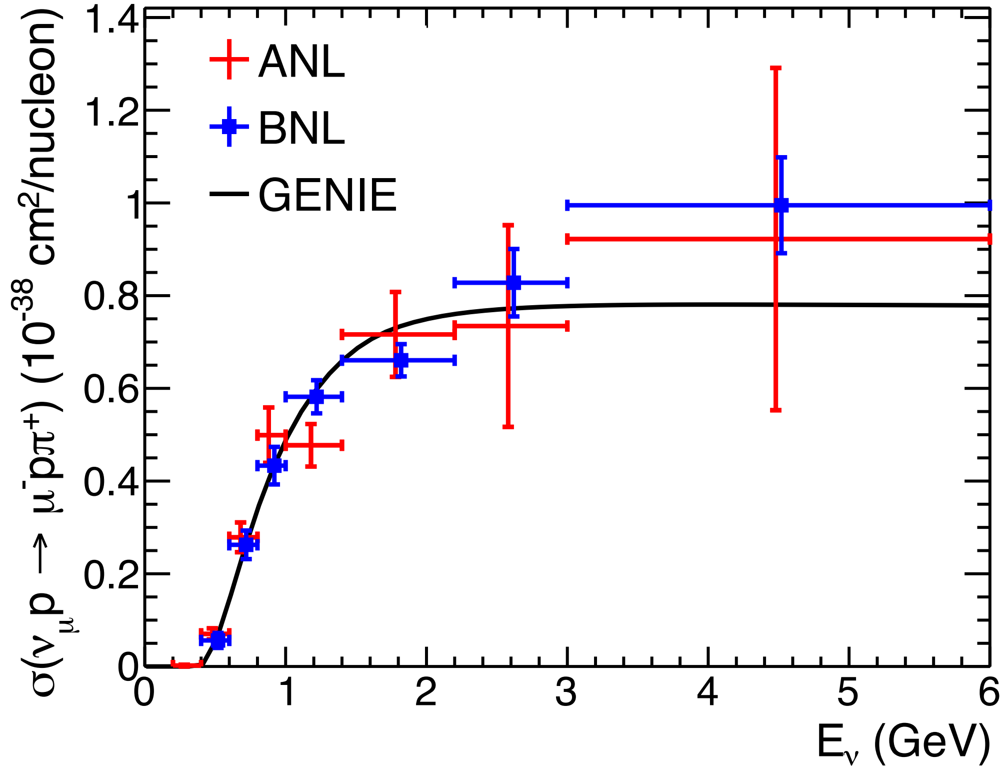
- Next important channel for neutrino oscillation and increasing the W toward the QCD limit
- Most experiments use the Rein-Sehgal model for νN resonance production
  - More recent models by M. Athar, Salamanca-Valencia, M. Pascos
- Experimentalist's dilemma: Whichever model you use, it will be poorly constrained by νN data

Old bubble chamber deuterium data



O. Lalakulich&U. Mosel, Nuint 12

Recent reanalysis of deuterium data finds consistency between ANL and BNL

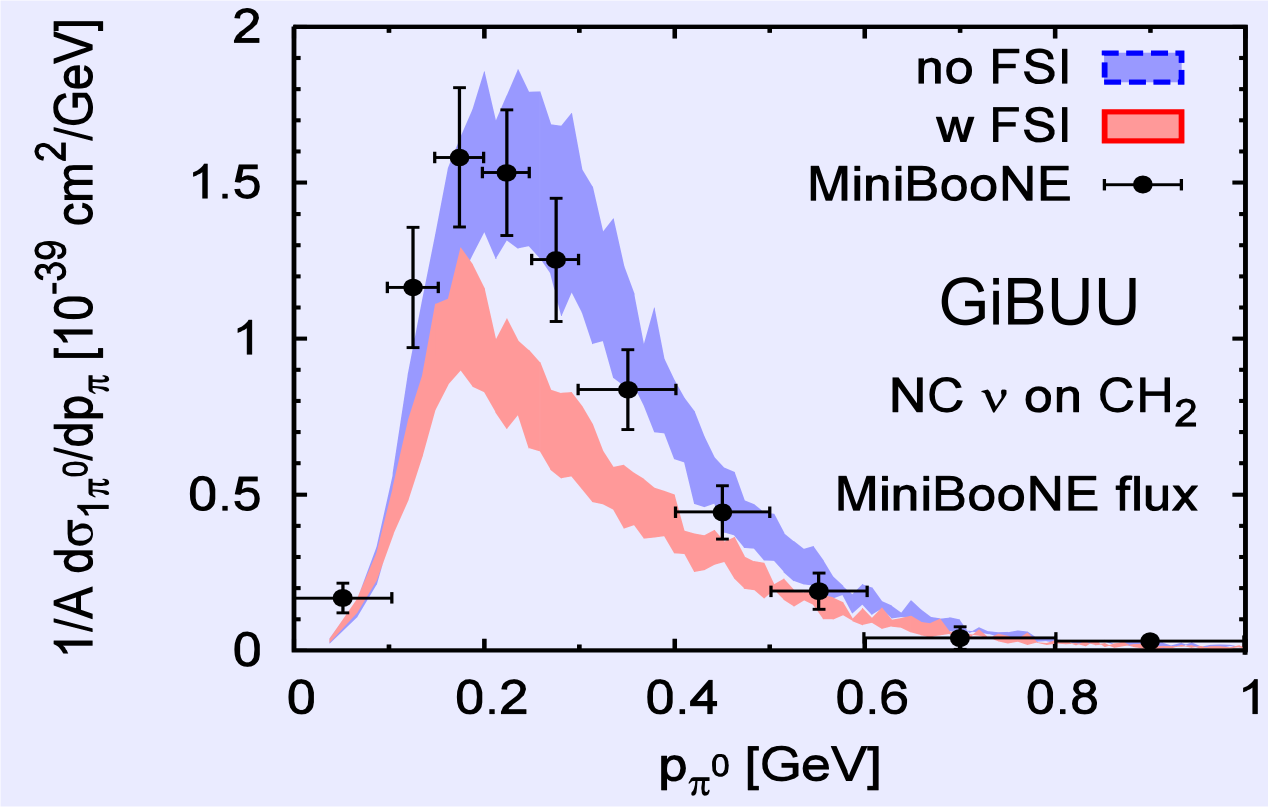


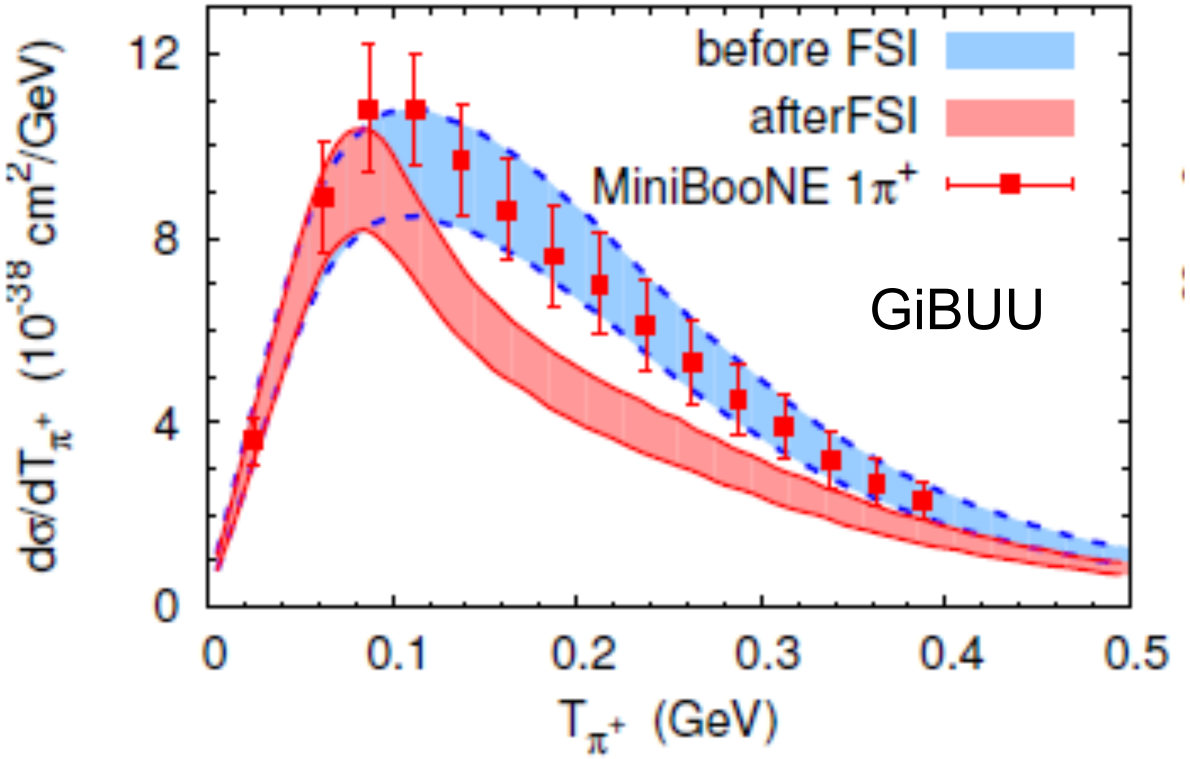
PRD 90, 112017 (2014)

- All the generator are tuned to bubble chamber deuterium data

Comparison of π^0 and $\pi^{\pm}$ Models with Data from MiniBooNE

- Data is compared against a theoretical model (GIBUU)
- Data prefers GIBBU with no final state interaction for both π^0 and $\pi^{\pm}$



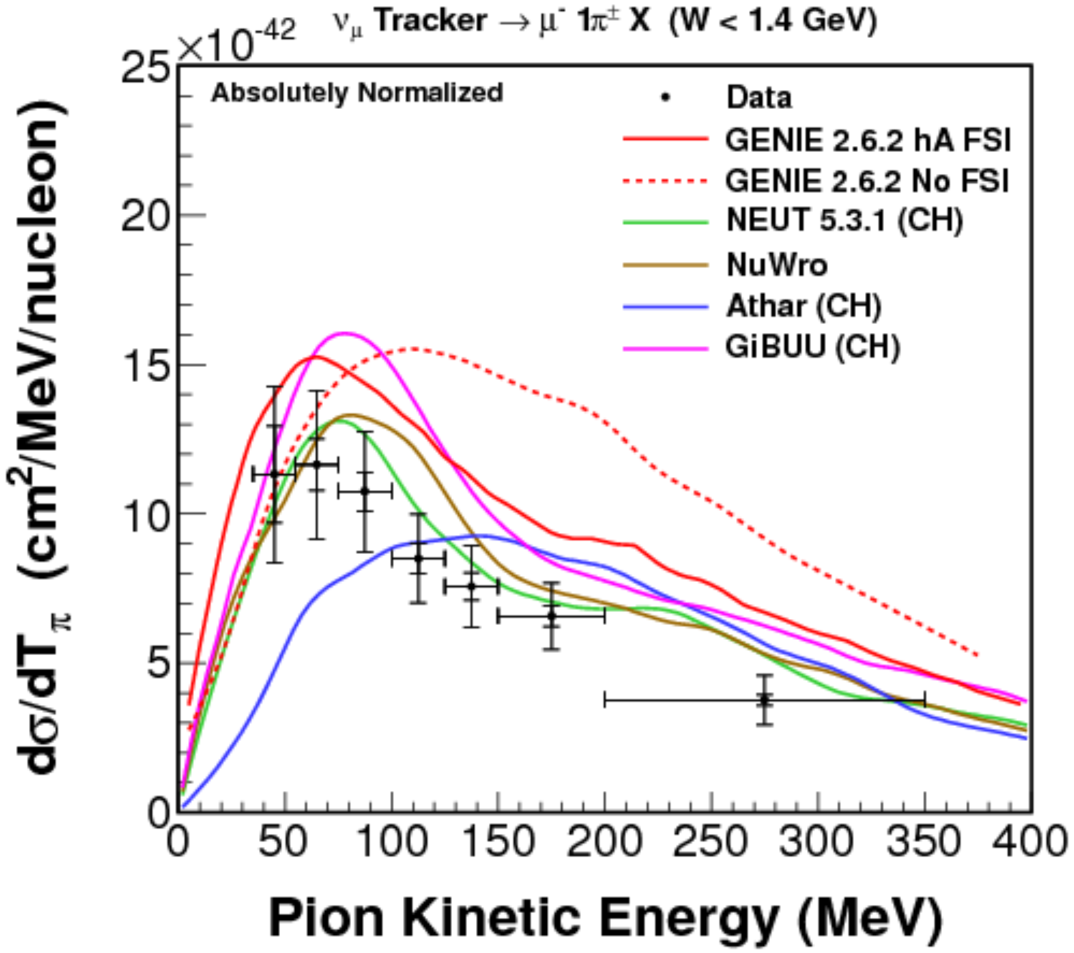


Lalakulich, Mosel , Phys.Rev. C 87 (2013) 014602

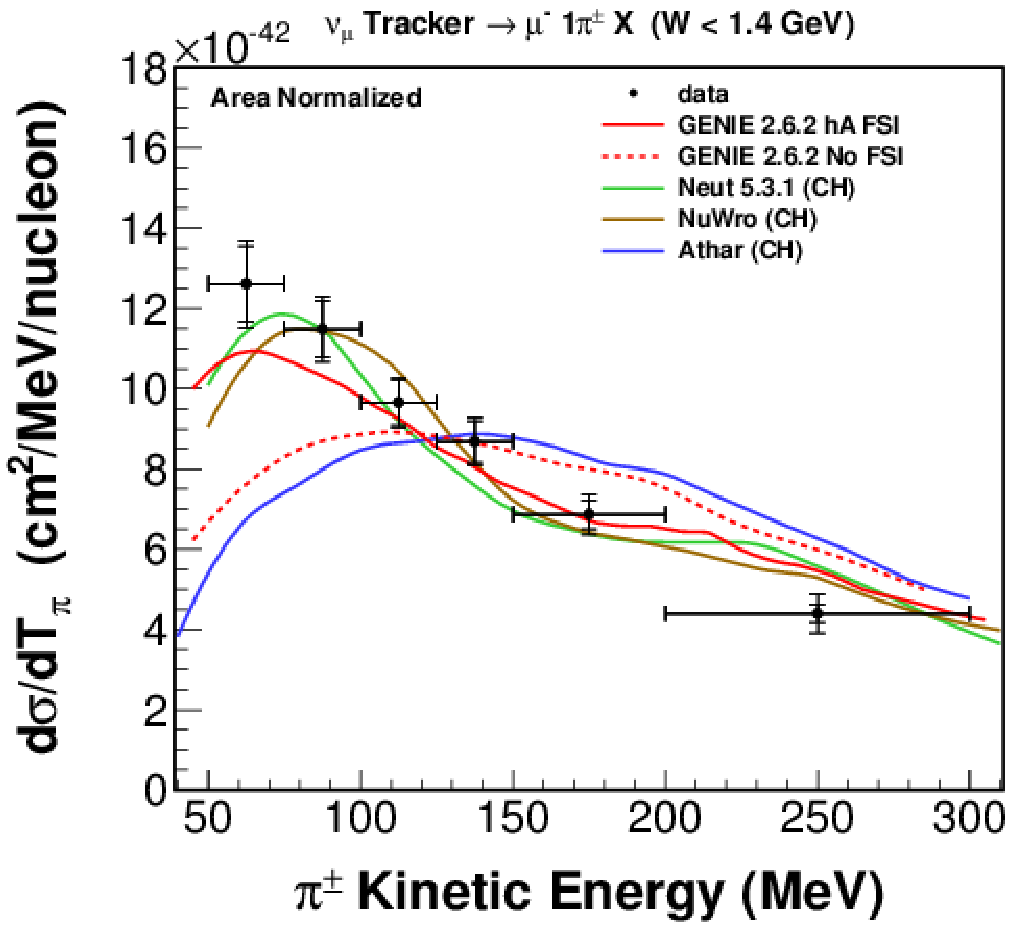
- We know there is final state interactions in both channels, but this is an excellent sample of how difficult is to untangle the underlying neutrino interaction model from nuclear effects

Comparison of neutrino $\pi^{\pm}$ Models with Data from MINERvA (W<1.4 GeV)

- Differential cross section as a function of pion kinetic energy, left absolutely normalized and right area normalized



NEUT and NuWro normalization agree the best with data GIBBU, GENIE normalization disfavored



GENIE (with FSI), NEUT, and NuWro predict the shape well. Except for Athar, data is unable to distinguish different FSI model

$$E_\nu = E_\mu + E_H$$

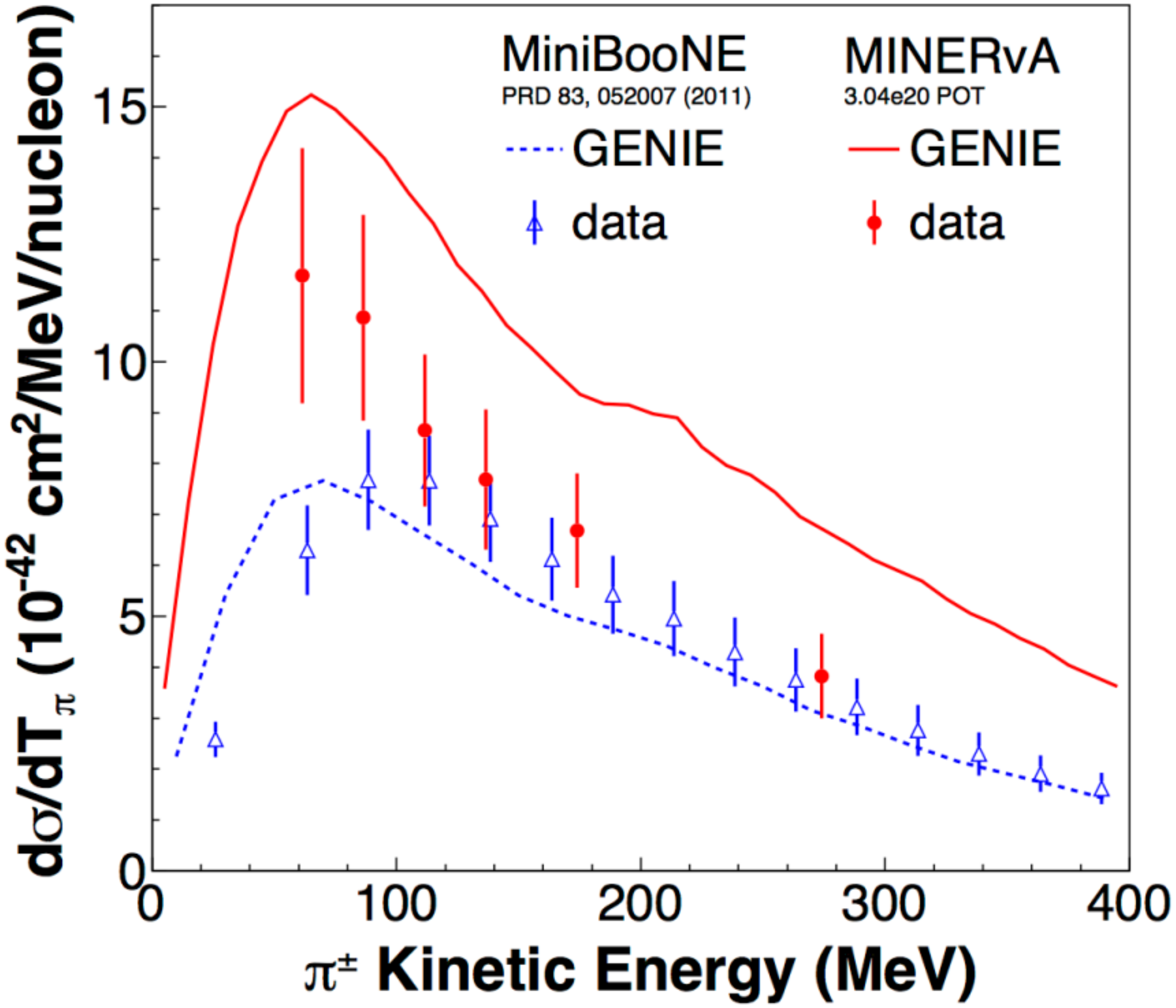
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

$$W_{exp}^2 = -Q^2 + m_p^2 + 2m_p E_H$$

arXiv:1406.6415

W<1.4 GeV Analyses

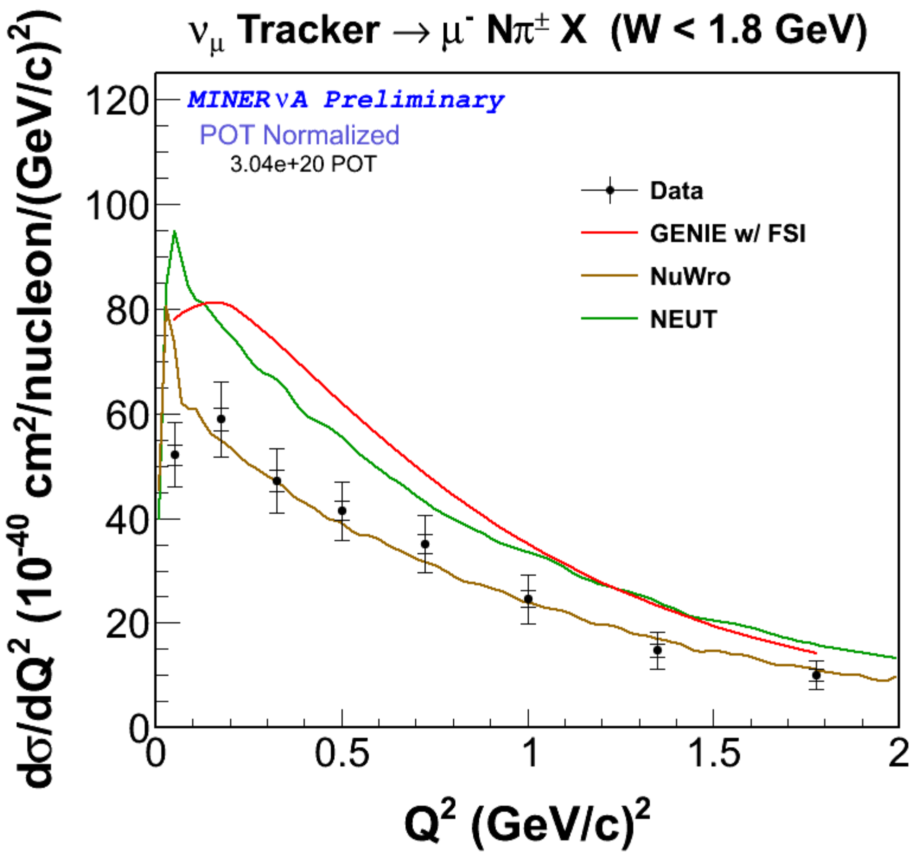
- No models describe all data sets well
  - MiniBooNE <E>=0.8 GeV: best theory models (GIBUU) strongly disagree in shape
  - MINERvA <E>=3.5 GeV: Event generator has shape but not magnitude

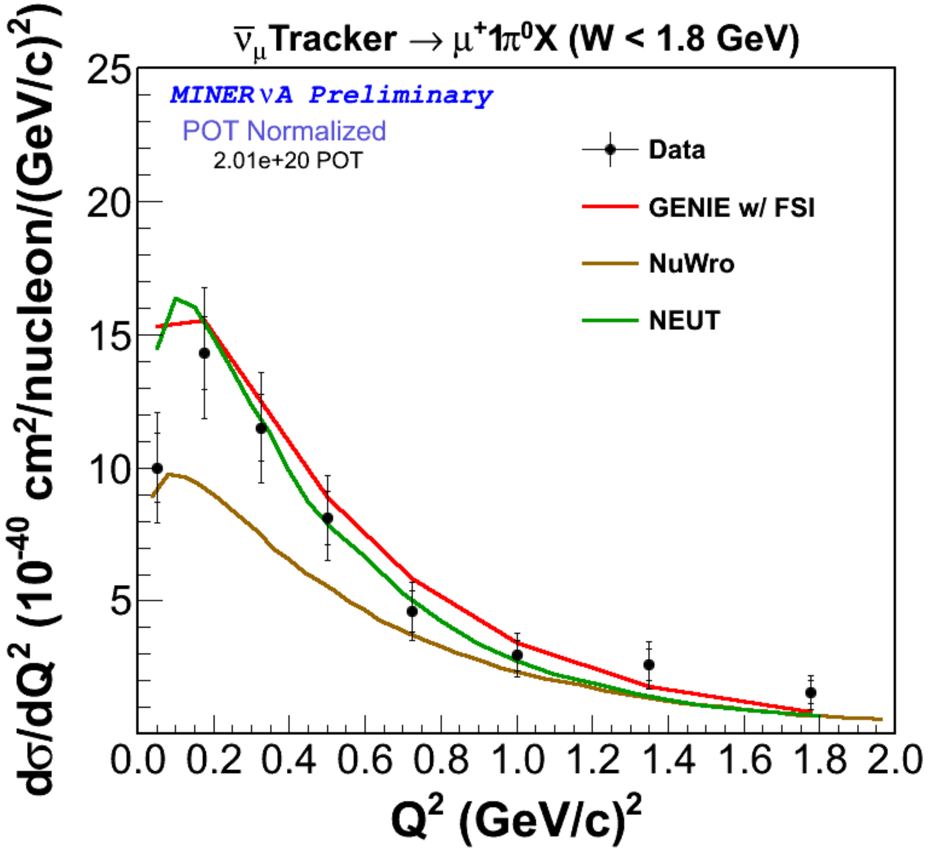


arXiv:1406.6415

Multi pi zone (W<1.8 GeV) at MINERvA

- Neutrino pion and antineutrino pi0 analyses for W<1.8 GeV
- Using the lepton information, these measurements are sensitive to nuclear structure



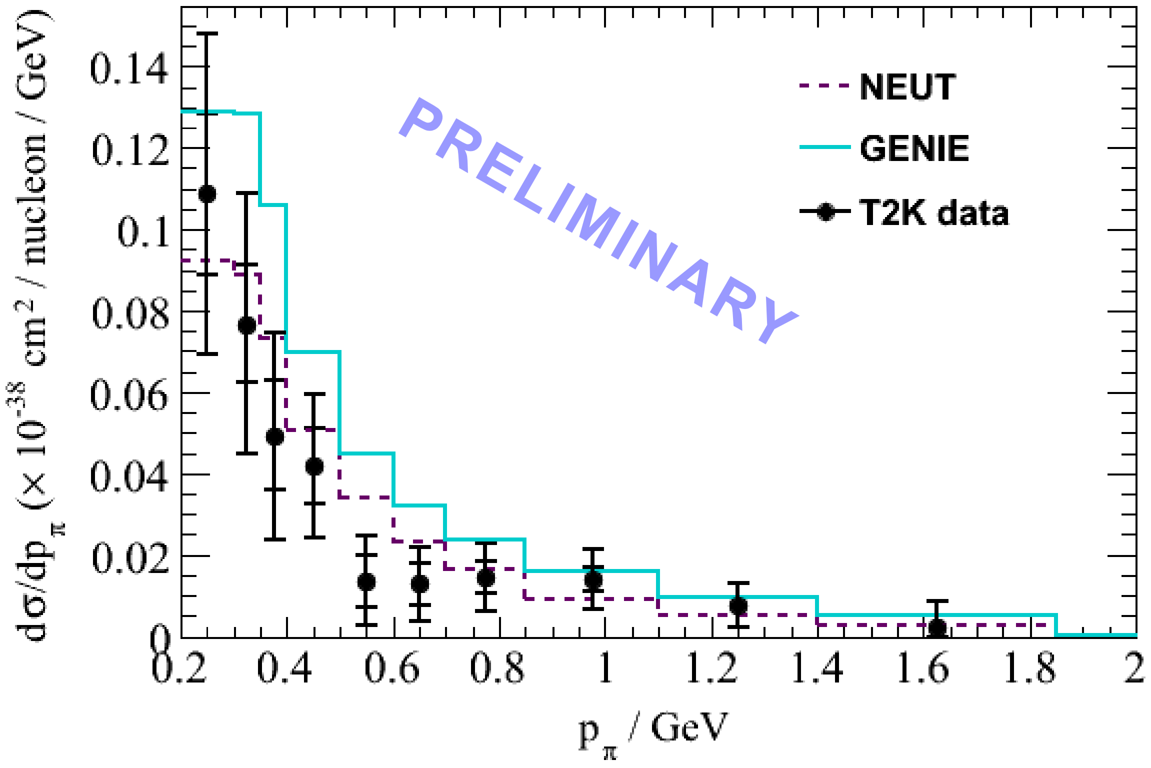


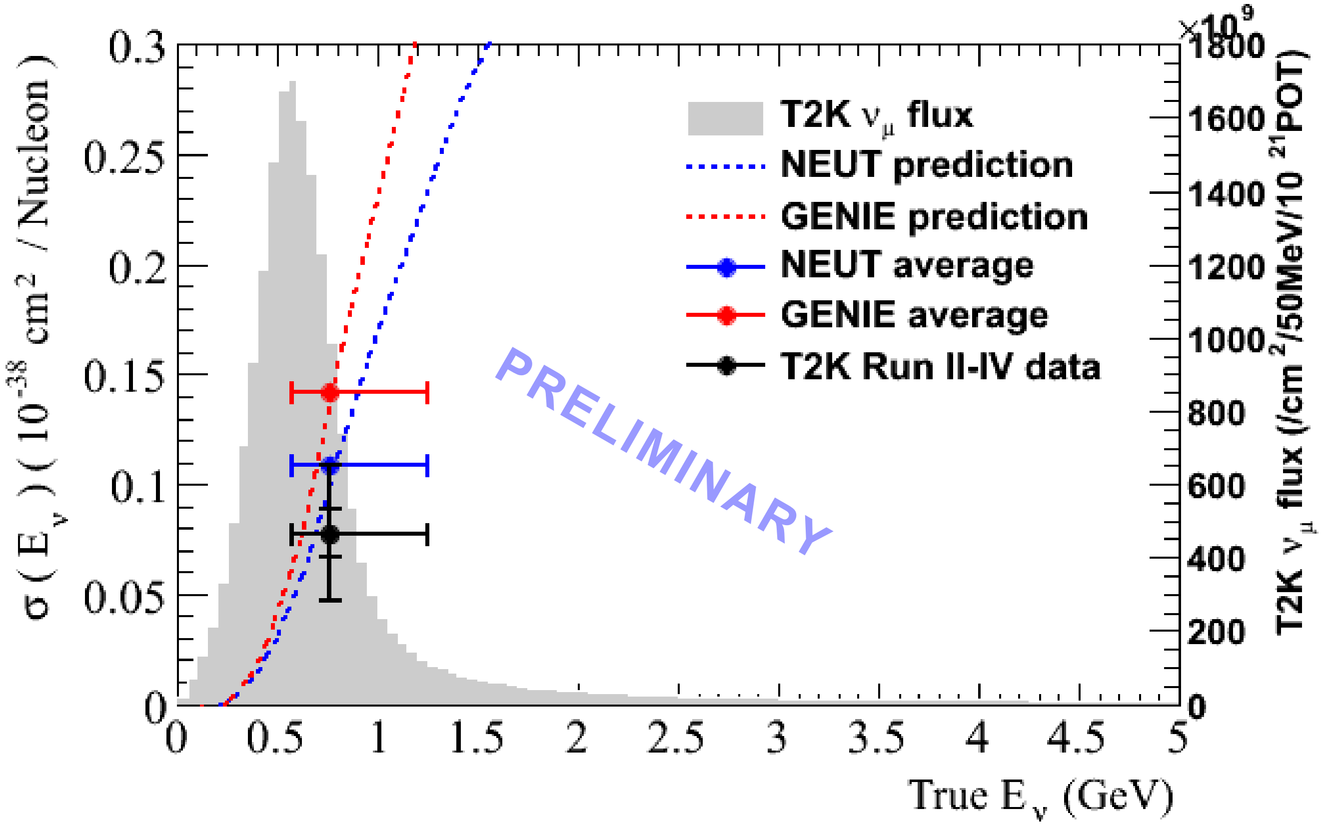
http://minerva-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=11203&filename=JTES_20150626.pdf&version=4

- In charged pion both GENIE and NEUT over estimate the cross section
- In neutral pions GENIE and NEUT agree better with data than NuWro, expect in the first bin
- The Q^2 spectrum provides the most detail and no single model describes both the charged and neutral distributions
- Experimental data pointing to the need of improved nuclear models

Charged Current 1π from T2K

- Results from T2K in the water target
  - Two track events in fiducial volume
- Main background are carbon and charged current non-1pi interactions





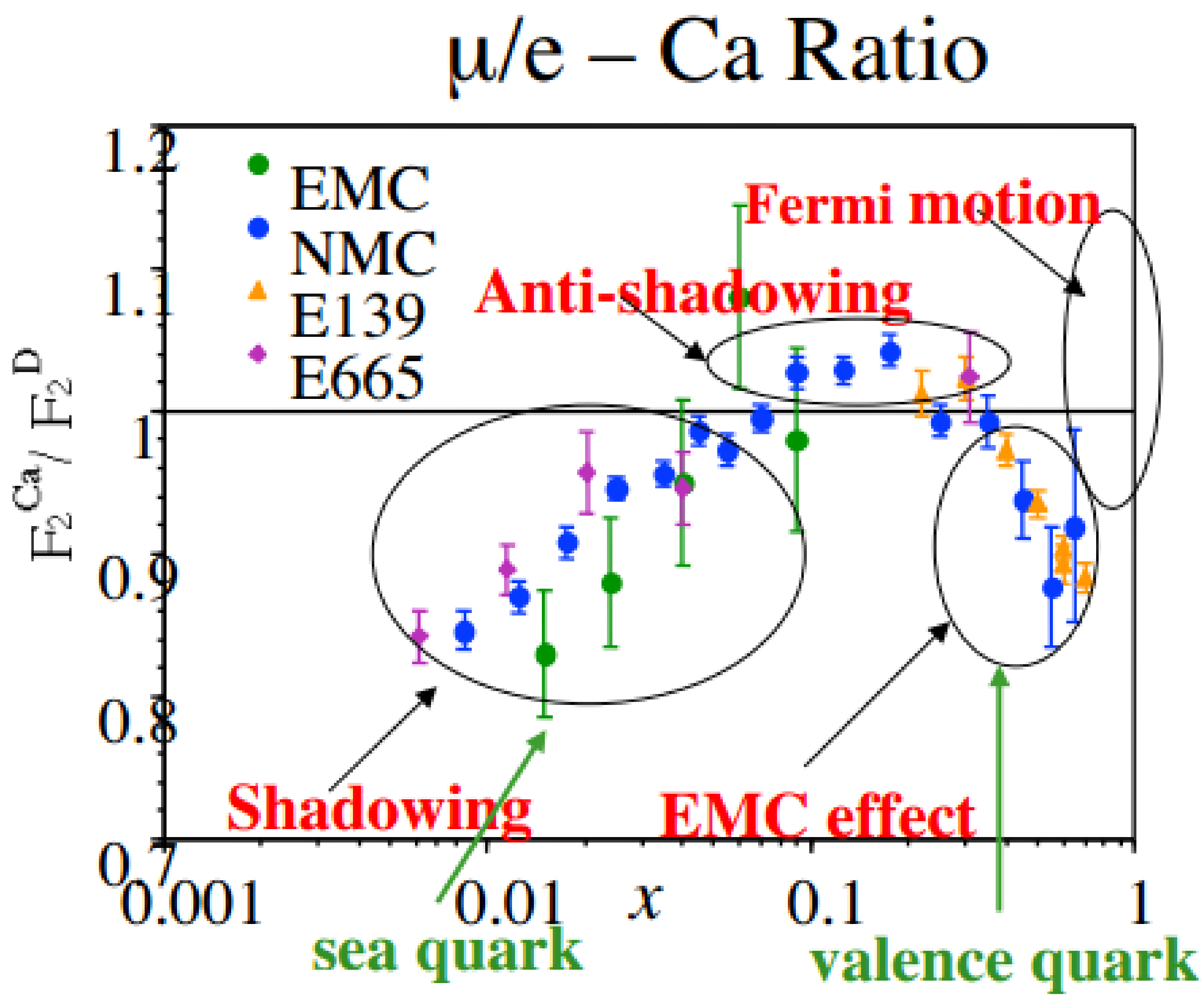
M. Nirkko, NuFact 2015

- The generators GENIE and NEUT overestimate the data

Charged Current Inclusive and Deep Inelastic Scattering (Ratios of scattering off nuclear targets)

Charged Lepton Nuclear Effects

- Reminder: F2/nucleon changes as a function of A
- Measured in μ/e - A not in $\nu - A$
- Neutrino event generator relies on measurements from charged leptons



$$x = \frac{Q^2}{2ME_{had}}$$

Scaling variable Bjorken x. In the parton model, x is the fractional momentum of the struck quark

Shadowing and Anti-shadowing: Depletion of cross section at low x, presumably compensated by enhancement from x~0.1-0.3. Shadowing is well understood experimentally and theoretically

EMC effect: no universally accepted cause(though many theories). What is known is that it is strong function of local nuclear density

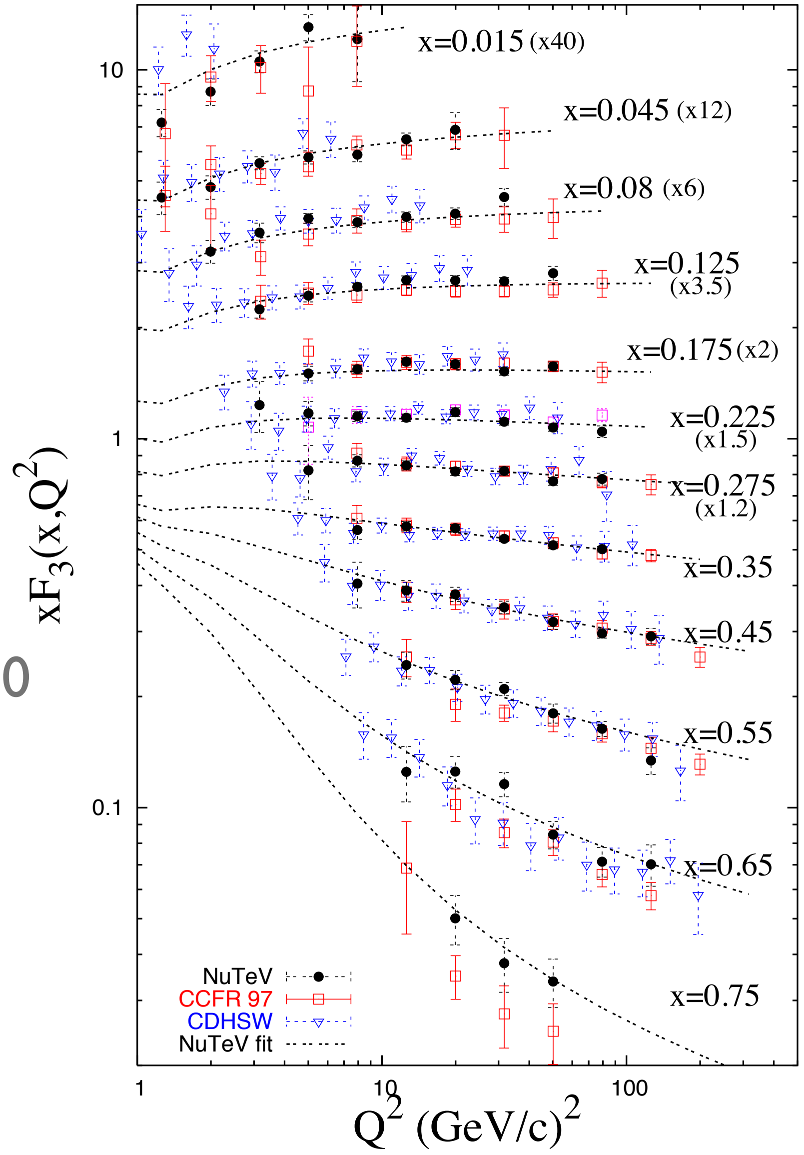
Fermi motion: Each quark is allowed to have a maximum momentum of x=A, so increasing A increases maximum allowable x

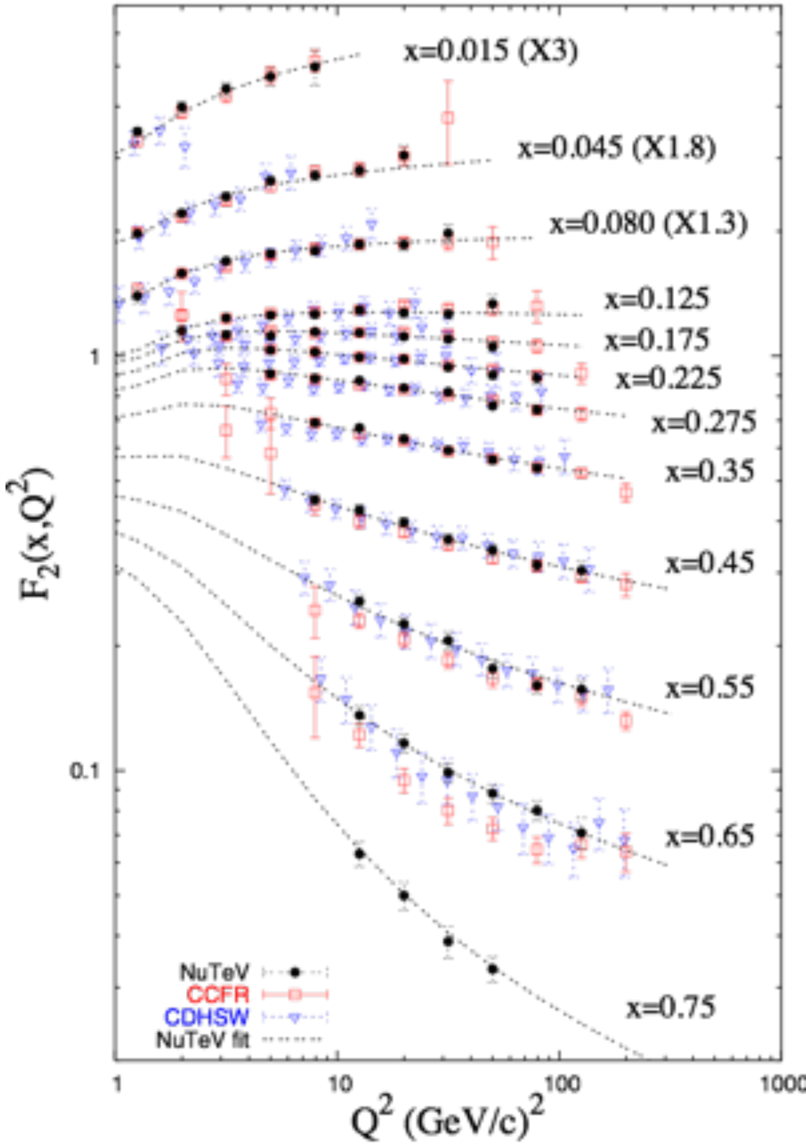
Neutrino Deep Inelastic Scattering off Iron from NuTeV

- The NuTeV experiment collected data using high purity neutrino and antineutrino with energies 30-500 GeV at Fermilab
- NuTeV used a calorimeter detector made of Iron and liquid scintillator
- Structure functions for iron are determined from fits to linear combinations of neutrino and antineutrino differential cross sections

$$\frac{d^2\sigma}{dxdy}^{\nu} + \frac{d^2\sigma}{dxdy}^{\overline{\nu}} = \frac{G_F^2 ME}{\pi}\Big[2\Big(1-y-\frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R_L}\Big)F_2 + y\Big(1-\frac{y}{2}\Big)\Delta xF_3\Big].$$

- At moderate x, NuTeV results agrees with CCFR data
- There is some disagreement for x>0.40



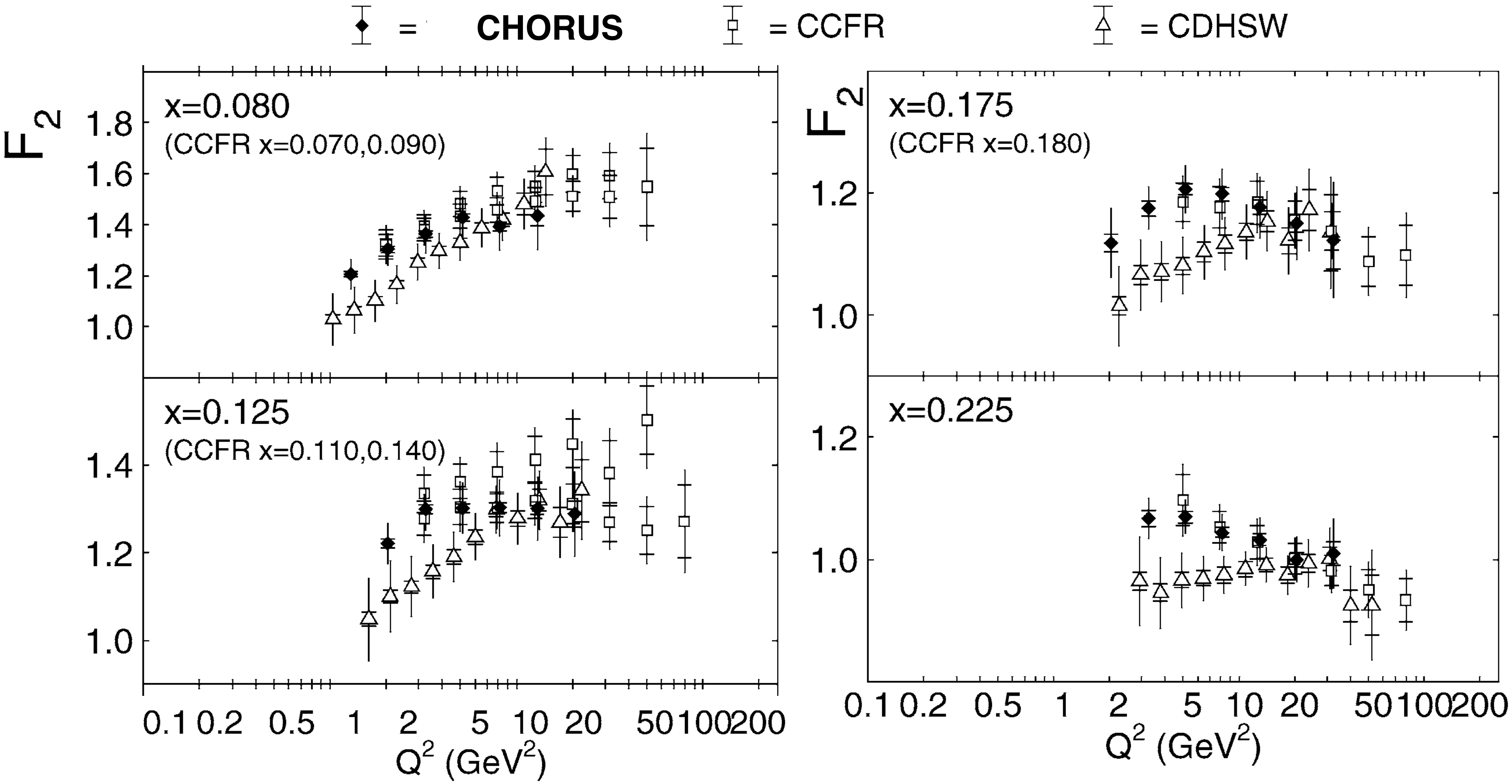


CCFR used the same detector as NUTeV in earlier experiment
CDHSW CERN experiment

Phys.Rev. D 74, 012008

Neutrino Deep Inelastic Scattering on Lead from CHORUS

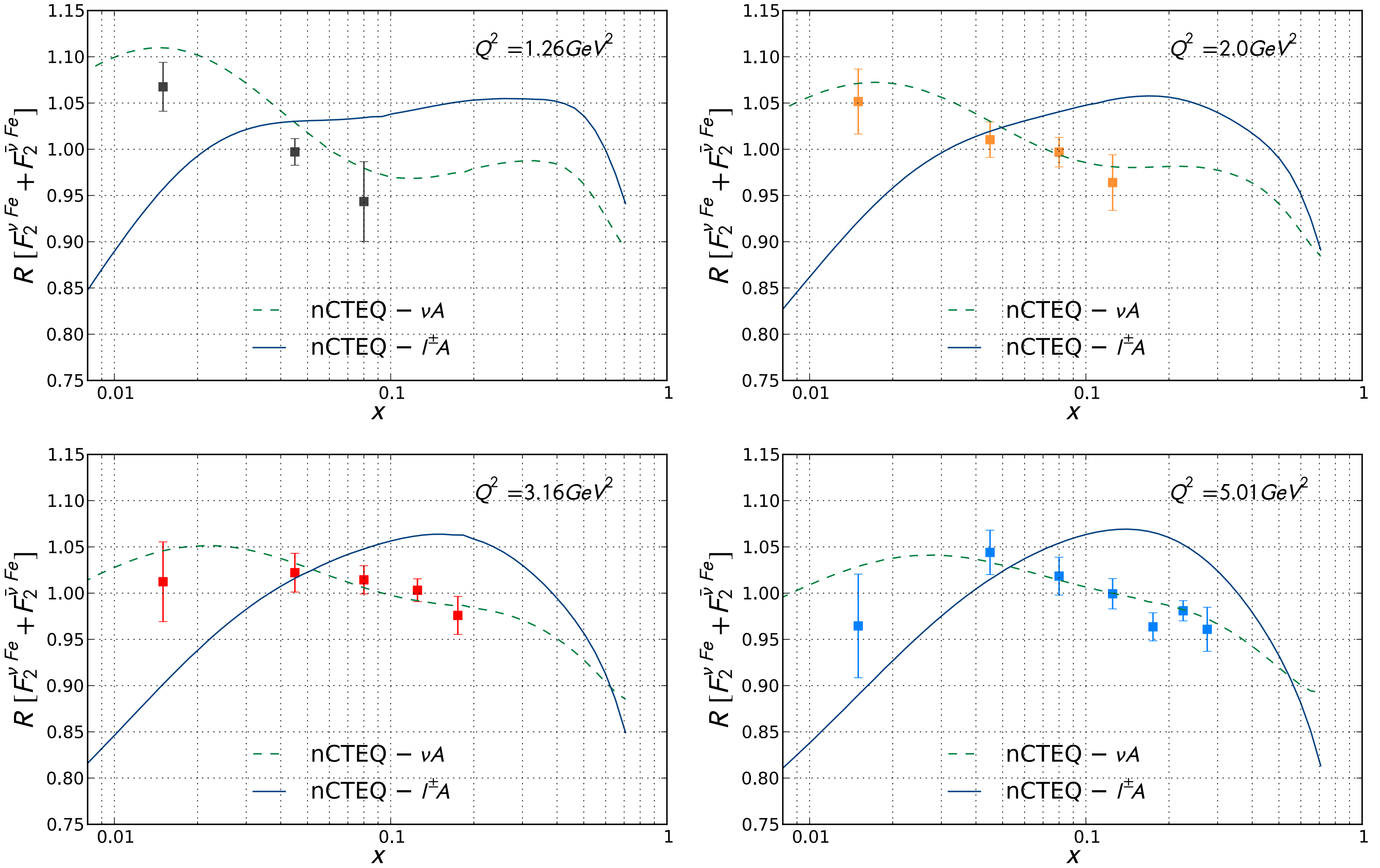
- The CHORUS experiment collected data using lead as target, high purity neutrino and antineutrino with energies 10-200 GeV
- Extract the neutrino lead structure functions
- The data for F_2 favors the CCFR data over the CDHSW data
- CHORUS measured the xF3 and reported the measurements agrees with CCFR and CDHSW



Physics Letter B 632 2006

Comparison of the IA and νA Nuclear Correction Factors

- An analysis from nCTEQ collaboration tries to fit for nuclear effects by comparing NuTeV structure functions on iron to predicted "n+p" structure functions and comparing to predictions from charged lepton effects
- Result show different behavior as a function of x, particularly in the shadowing region
- Low Q^2 and low x neutrino data cause tension with the shadowing observed in charged lepton data

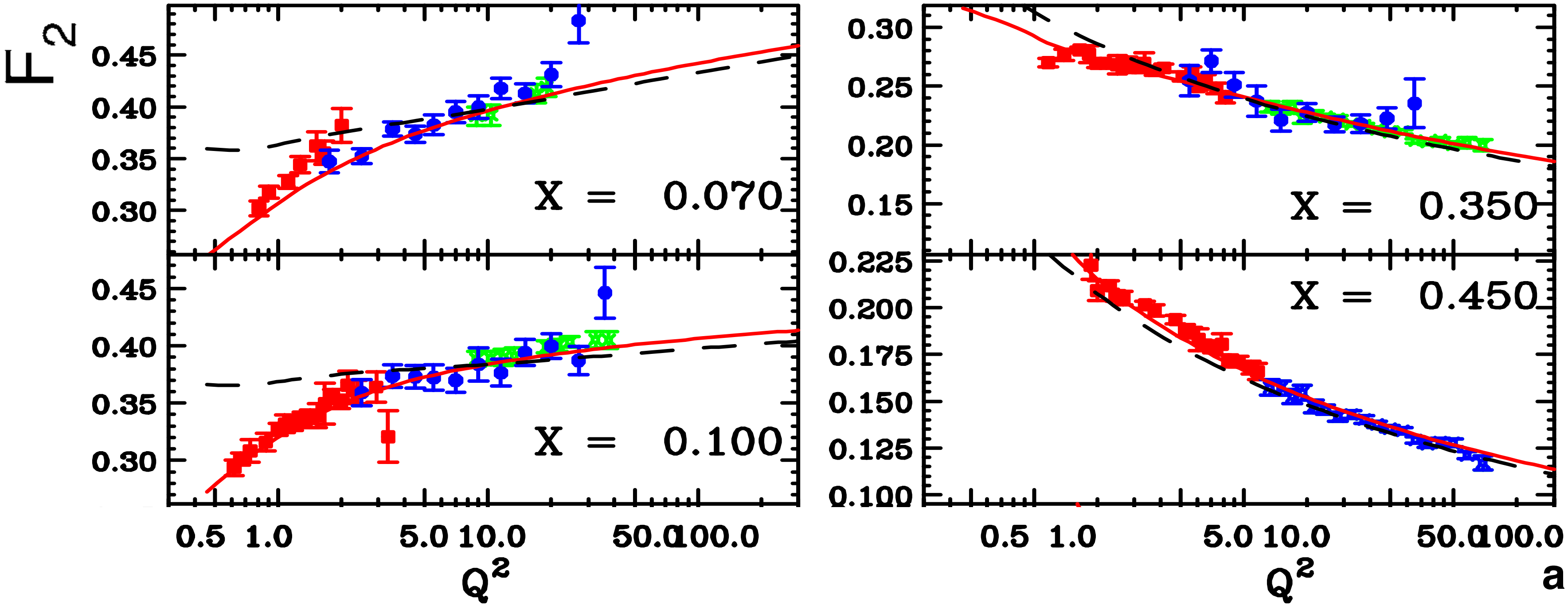


K. Kovarik et al. Phys. Rev. Lett 106:122301,2001

Transition Region between RES and DIS

- Bodek and Yang have introduced a refined model which is used by many of the neutrino event generator
- The model has been developed for both neutrino and electron nucleon inelastic scattering cross sections using leading order parton distribution function

Bodek and Yang's model compared to charged lepton F_2 experimental data (SLAC,BCDMS and NMC)



arXiv:1011.6592[hep-ph]

Dashed lines are from parton distributions obtained with a global fit (GRV98) and solid red lines are Bodek and Yang's fit

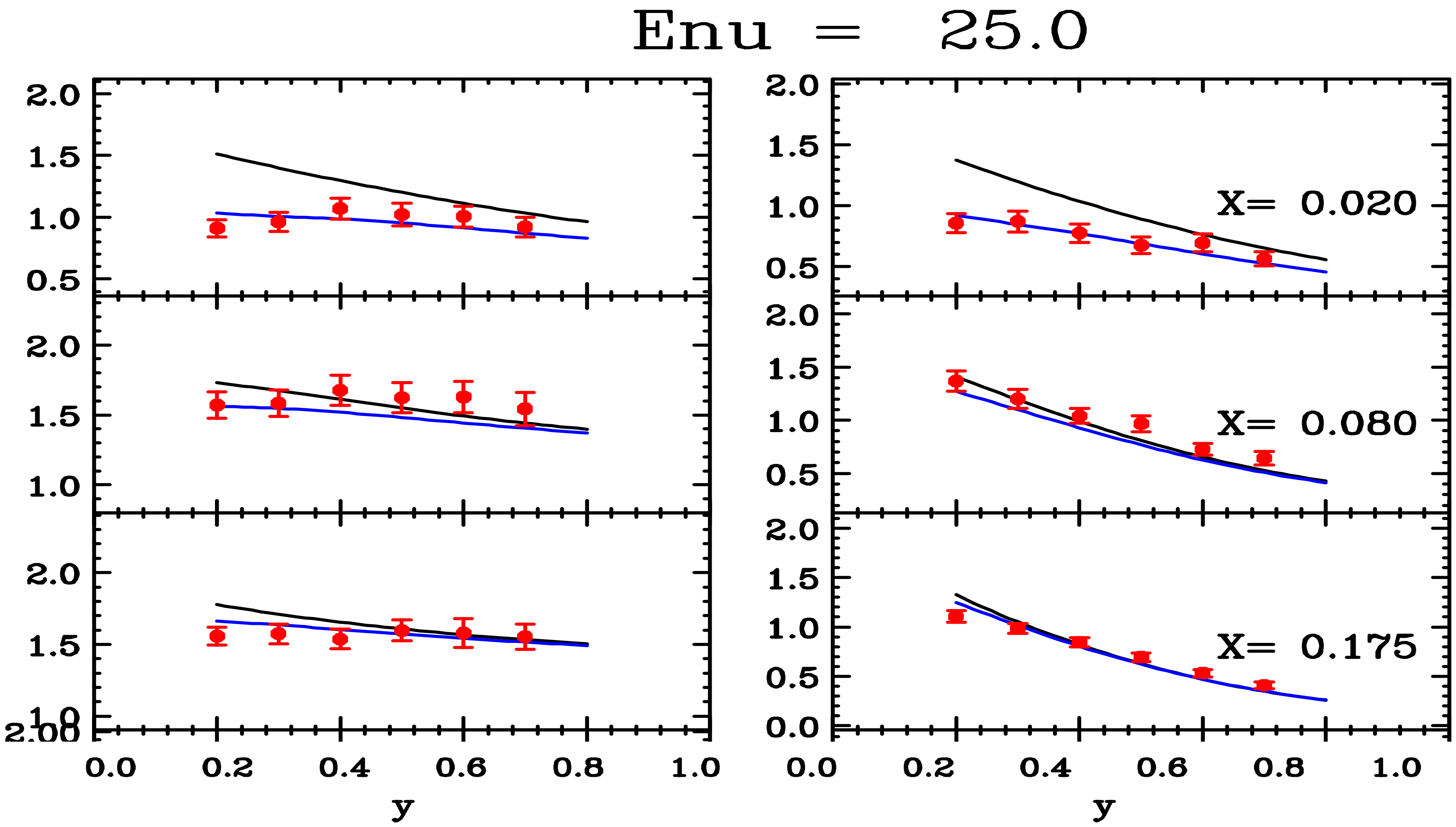
- The model describes the inelastic electron and muon F_2 data in proton and deuteron targets

Transition Region between RES and DIS

- Comparison of the Bodek and Yang model to neutrino data from on lead (CHORUS) and iron CCFR show good agreement
- Ratios of $d^2\sigma/dxdy$ to the default model shown in black and the blue is the ratio of a modified version of the model for which the axial structure functions are set equal to the vector structure functions

Neutrinos

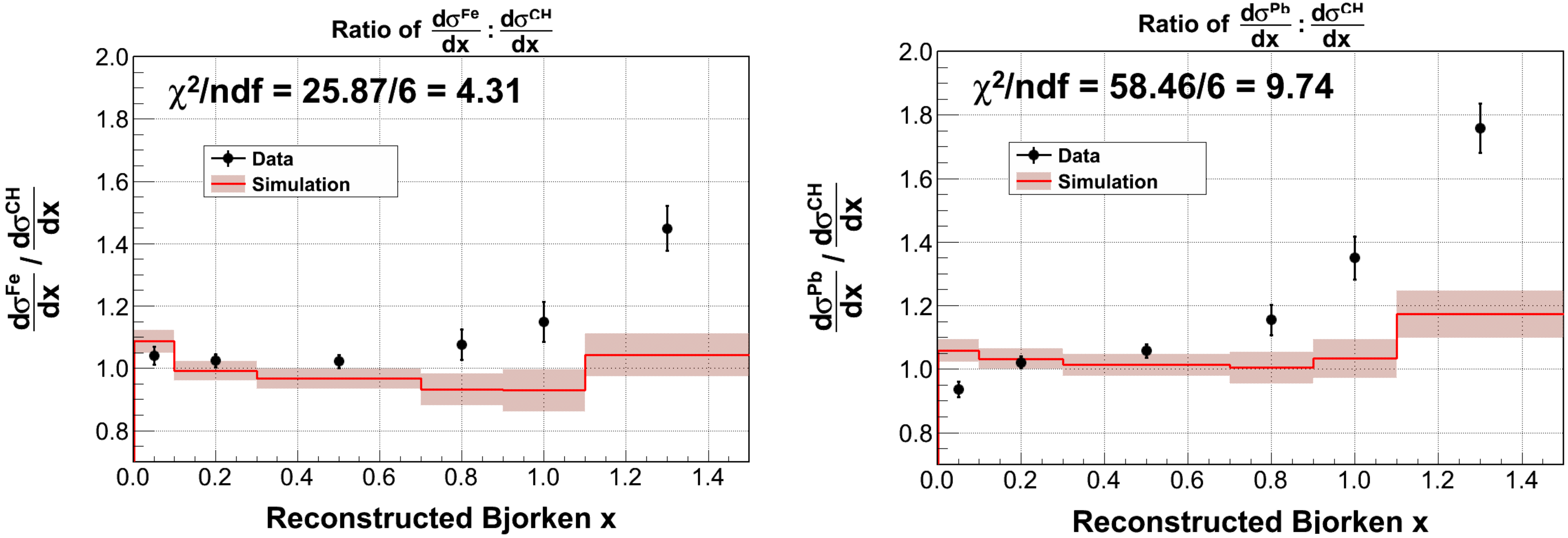
Anti-Neutrinos



arXiv:1011.6592[hep-ph]

Ratio between nuclear targets (CC Inclusive, not just DIS) from MINERvA

- MINERvA is starting to study X dependent nuclear effects with neutrinos, unique experiment with different nuclear targets iron, lead and carbon
- Measurements of CC inclusive ratios for iron to scintillator and lead to scintillator

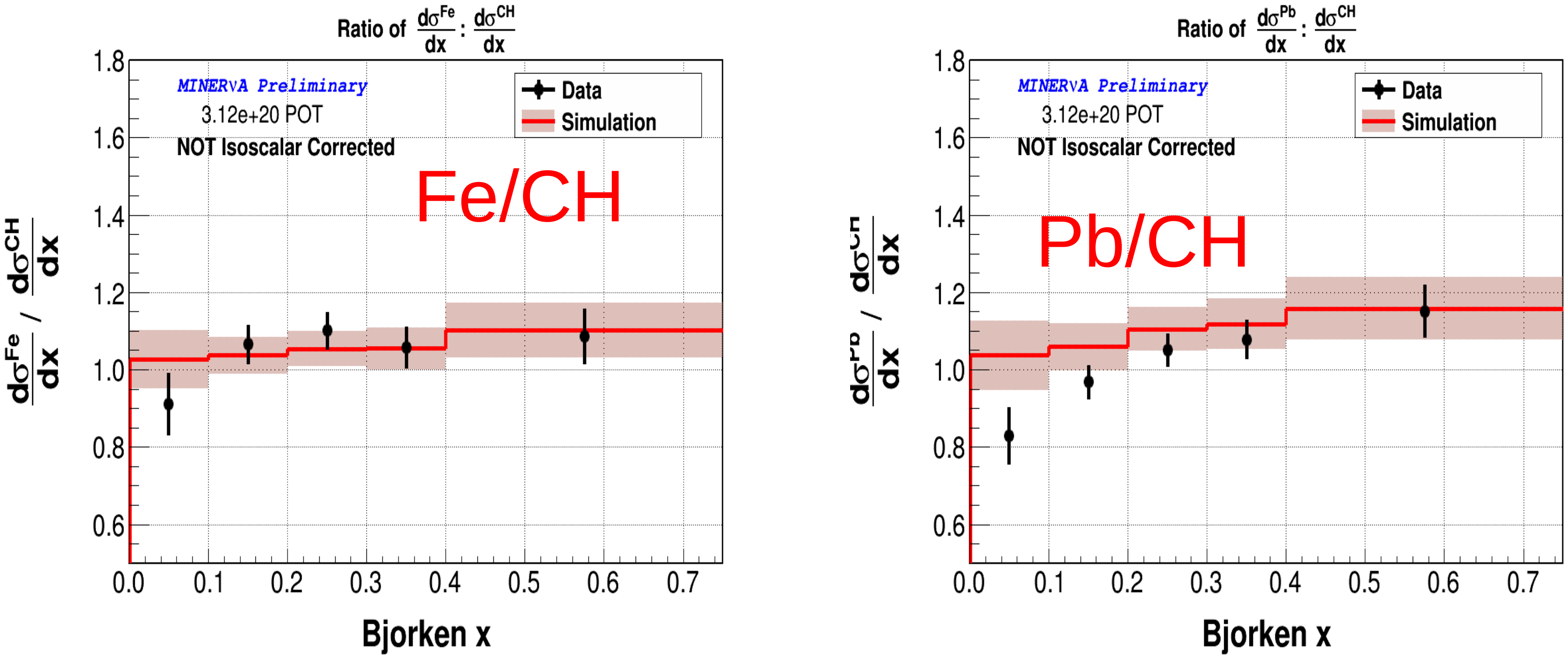


Phys. Rev. Lett. 112, 231801 (2014)

- Disagreement between data and GENIE generator.
- The high X region is dominated by the quasi-elastic and resonance production
  - This suggests we do not model well the A dependence of the quasi-elastic and resonance channels which are dominant for the oscillation experiments
- We need better understanding the A dependence of inclusive scattering

Deep Inelastic Scattering from MINERvA

- MINERvA produced deep inelastic ratios from nuclear targets to study x dependent nuclear effects using the low energy data that has restricted DIS statistics
- We have a x range from the low x shadowing region through the EMC region
- The simulation used in the analysis assumes the same x-dependent nuclear effects for C, Fe and Pb based on charged lepton scattering



http://minerva-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=11041&filename=MousseauJTEP.pdf&version=1

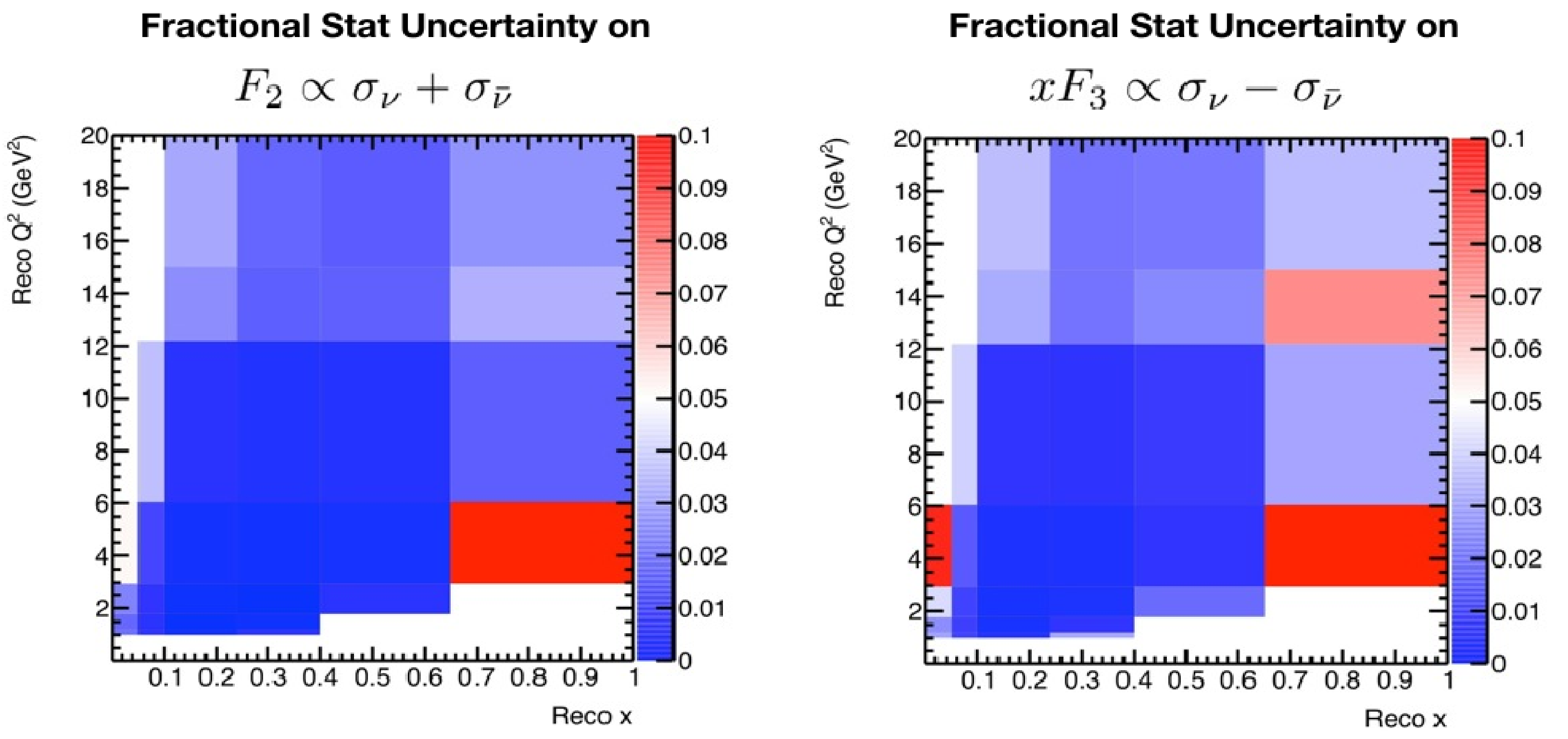
- The data suggest additional nuclear shadowing in the lowest x bin (0<x<0.1) than predicted in lead, it is at a value of x and Q2 where shadowing is not normally found in charged lepton nucleus scattering
- In the EMC region (0.3<x<0.75), we see good agreement between data and simulation

Structure Function Extraction at MINERvA

- MINERvA is collecting data using a higher energy beam. This data set will be used to extract the nuclear structure functions for neutrinos

$$\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)}\left[\frac{y^2}{2}2x\boxed{F_1^{\nu(\bar{\nu})A}} + \left(1-y-\frac{Mxy}{2E_\nu}\right)\boxed{F_2^{\nu(\bar{\nu})A}} \pm y\left(1-\frac{y}{2}\right)\boxed{xF_3^{\nu(\bar{\nu})A}}\right]$$

Three structure functions describe the ν_μ + **A** and $\bar{\nu}_\mu$ + **A** DIS cross section


Fractional Stat Uncertainty on $F_2 \propto \sigma_\nu + \sigma_{\bar{\nu}}$

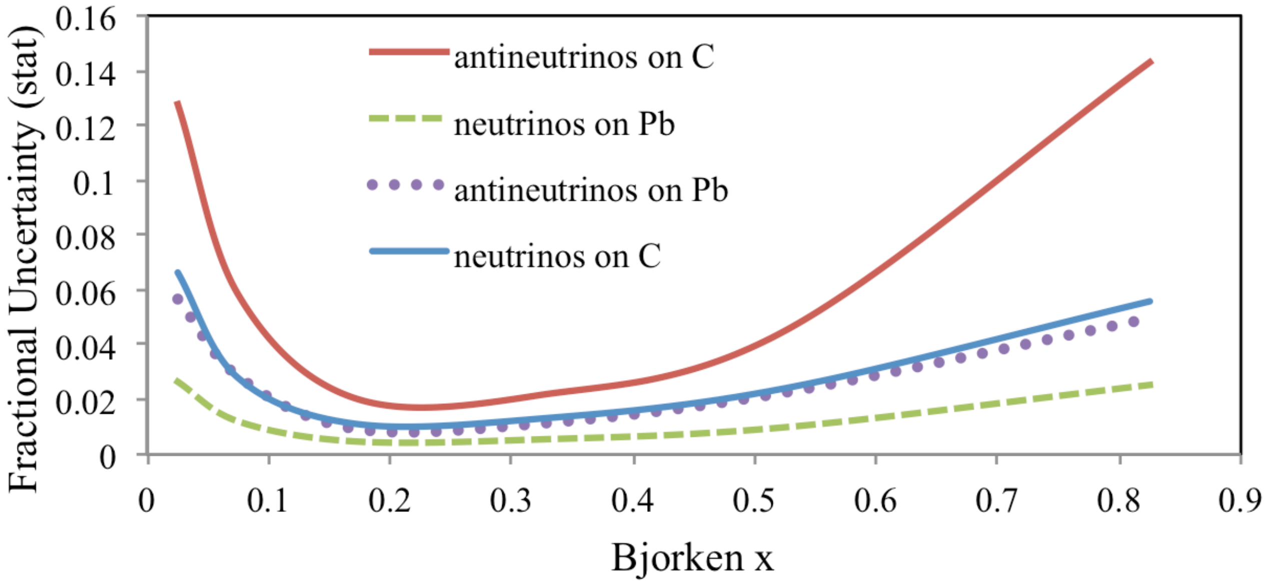
Fractional Stat Uncertainty on $xF_3 \propto \sigma_\nu - \sigma_{\bar{\nu}}$

12E20 POT Exposure

- We expect better than 10% accuracy for structure function extraction

Study of EMC Effect with MINERvA in the Medium Energy Beam

- Predictions for the fractional uncertainties for neutrinos and antineutrinos from MINERvA

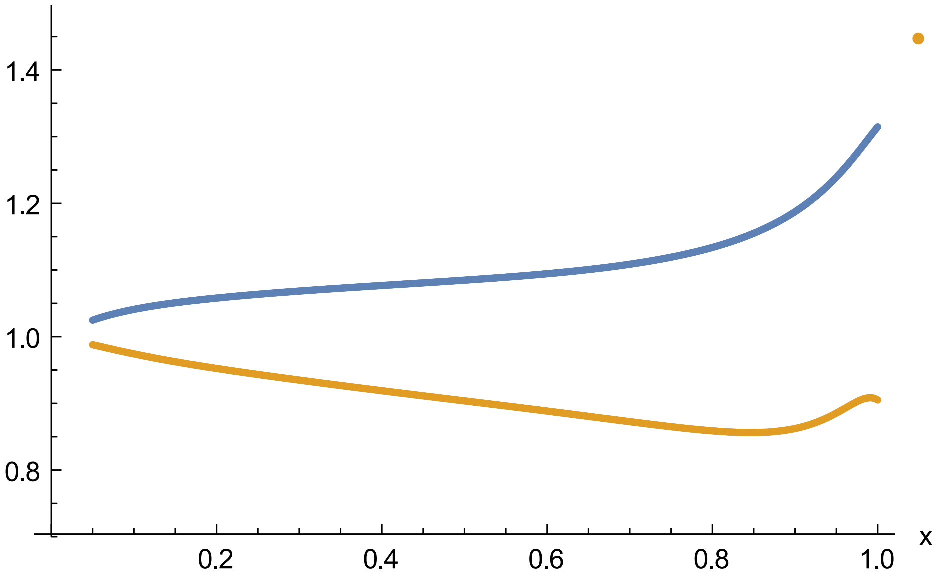


10E20 in neutrino mode and
12E20 antineutrino mode

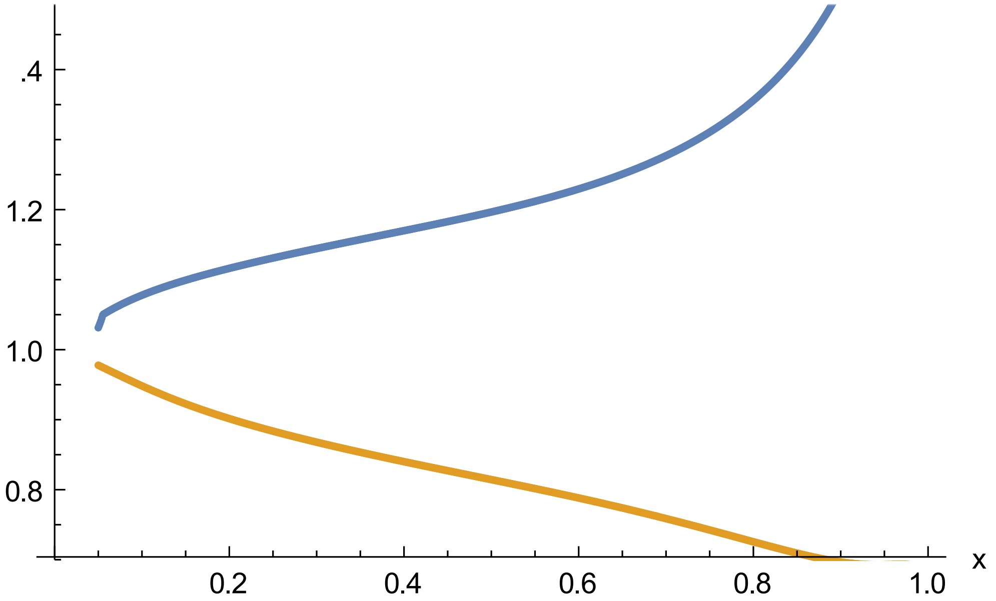
Prediction from Cloet model, **PRL 109, 182301,** shadowing is not include

Ratio of Iron to CH cross section

- ● Neutrino
- ● Antineutrino

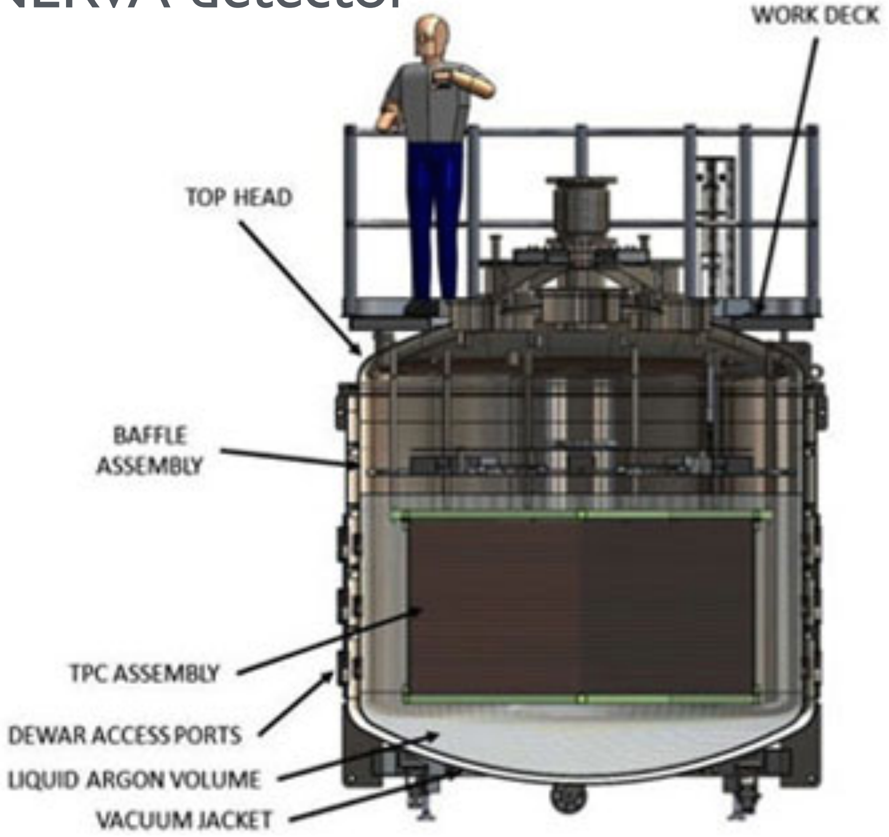


Ratio of Lead to CH cross section



New Construction and Upgrades from MINERvA

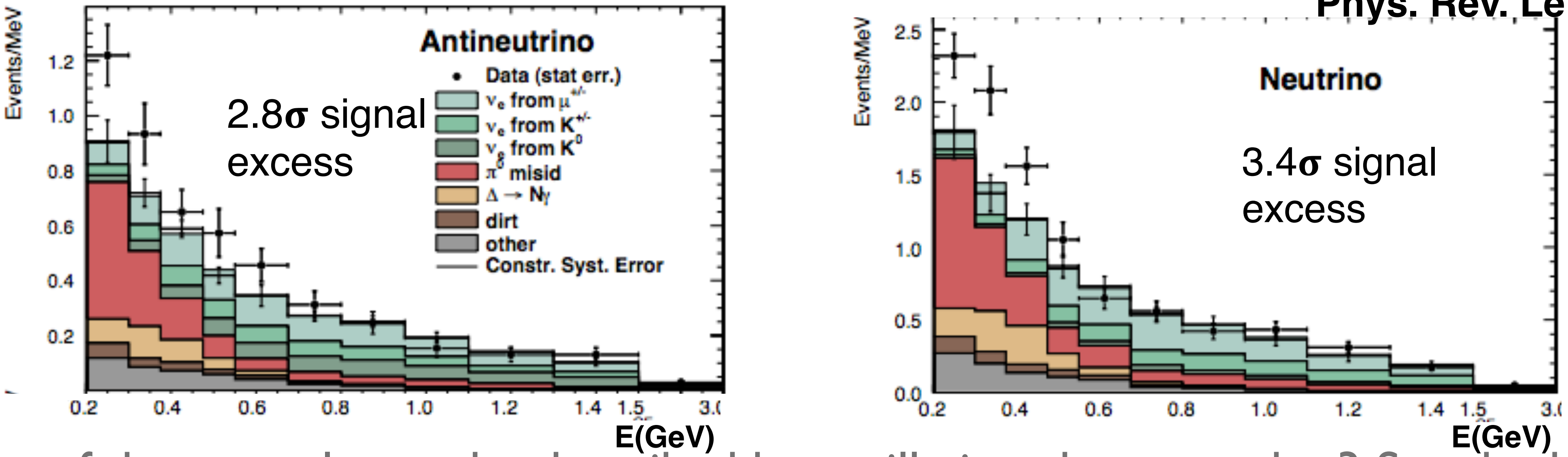
- Strong program aim to understand neutrino scattering in LArTPC: CAPTAIN + MINERvA
  - The proposal is to place the CAPTAIN LArTPC in front of MINERvA detector
  - High statistics measurements of neutrino interactions on argon in the medium energy range (high statistic for deep inelastic interactions)
  - Unique results that will help to constrain models before DUNE
  - CAPTAIN-MINERvA can measure cross section ratios for example argon to carbon
  - Study how processes vary on different nuclei
  - More precise test of the models can be performed with ratios due to cancelation of large systematic uncertainties such as neutrino flux



- MINERvA is collecting more data with the medium energy beam from NOvA and aim to extract structure functions and measure partonic nuclear effects using antineutrino data

Future Experiments

- Study neutrino anomalies and sterile neutrinos
  - Two classes of anomalies pointing at additional physics beyond the standard model in the neutrino sector
    - The apparent disappearance signal in the low energy anti-neutrinos from nuclear reactors
    - Evidence for an electron-like excess in interactions coming from neutrinos produce in accelerators (LSND and MiniBooNE anomalies)



Phys. Rev. Lett. 110, 161801 (2013)

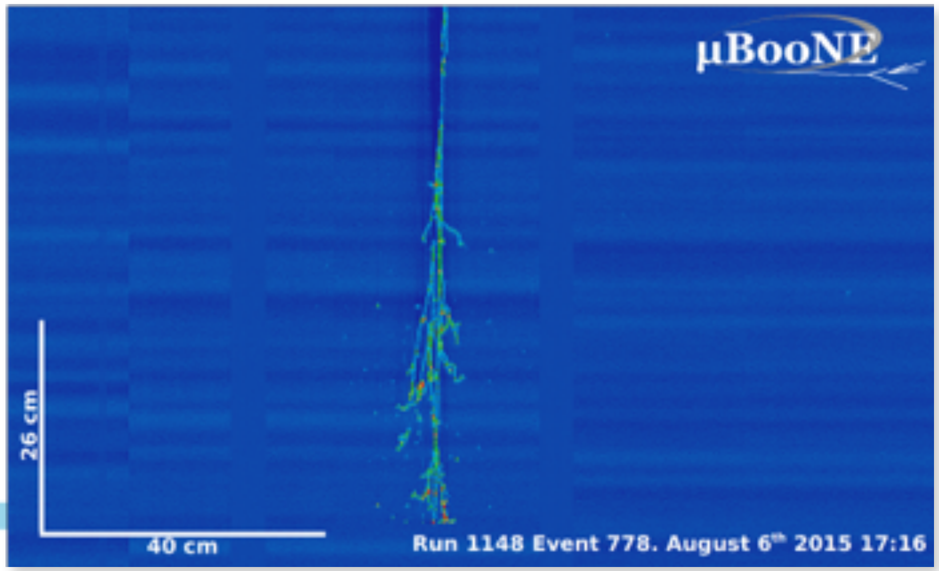
- None of these results can be described by oscillations between the 3 Standard model neutrinos
- The current short baseline program at Fermilab will use the Booster neutrino beam and different detectors MicroBooNE, SBND and ICARUS
- In addition, these experiments will be use to measure cross sections

MicroBooNE Experiment

- 170 ton LAr TPC in the Fermilab

- physics goals:
  - *address MiniBooNE low energy excess*
  - *make 1st low energy neutrino cross section measurements on argon*
- R&D goals:
  - *argon fill without evacuation*
  - *cold front-end electronics*
  - *long drift (2.5m)*
  - *near surface operation*
  - *event reconstruction*

- Booster Neutrino Beamline MicroBooNE is an important step in the development of large scale LAr TPCs for future short and long baseline ν physics
- Status:
  - detector was purged, cooled, and filled with liquid argon this past summer
  - on Aug 6, 2015: MicroBooNE saw first tracks!
  - continuing to develop analysis tools to be ready for first physics analyses
  - neutrino data-taking will begin when beam returns on Oct 5th
- MicroBooNE will make the first σ_ν measurements in ^{40}Ar at low energy (E_ν ~1 GeV). These analyses will benefit from the well-known BNB flux
- Statistics is huge, for 6 months: CC inclusive 26226, CC 0pi 16757

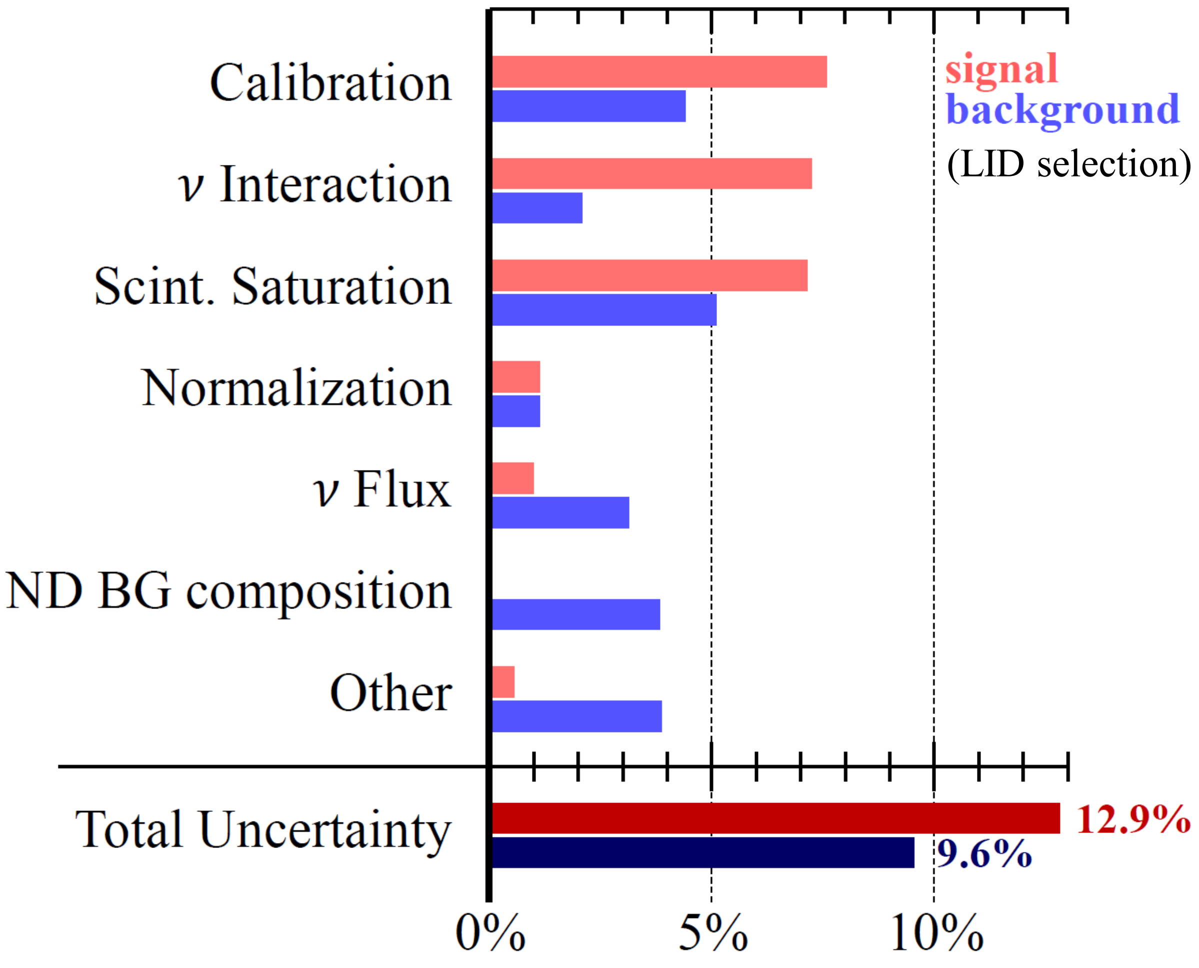


Summary

- Neutrino experiments have been making an excellent progress
  - Cross section experiments are producing accurate cross section measurements
  - Neutrino oscillation experiments have started to make precision measurements and search for CPV and mass hierarchy
- We need more theoretical contributions, have made progress with understanding neutrino scattering data, but still we have huge disagreement with models
  - Axial form factor for quasi-elastic
  - Better nuclear models for quasi-elastic and pion production scattering
  - We need a better understanding of the A dependence for CC inclusive scattering and deep inelastic
- In addition, contributions from QCD will be important for higher energy neutrinos, for example IceCube experiment
- For the coming years we will have high neutrino data statistics to test new models and test contributions from QCD

Systematic Uncertainties

Electron Neutrino Appearance Uncertainty from NOvA



Uncertainties from T2K

uncertainties	ν_μ disap.	ν_e app
ν flux+xsec (before) after ND constraint	(21.7%) ±2.7%	(26.0%) ±3.2%
ν unconstrained xsec	±5.0%	±4.7%
Far detector	±4.0%	±2.7%
Total	(23.5%) ±7.7%	(26.8%) ±6.8%