Fermilab

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Overview of Intensity-Frontier Efforts

Minerba Betancourt, Fermilab

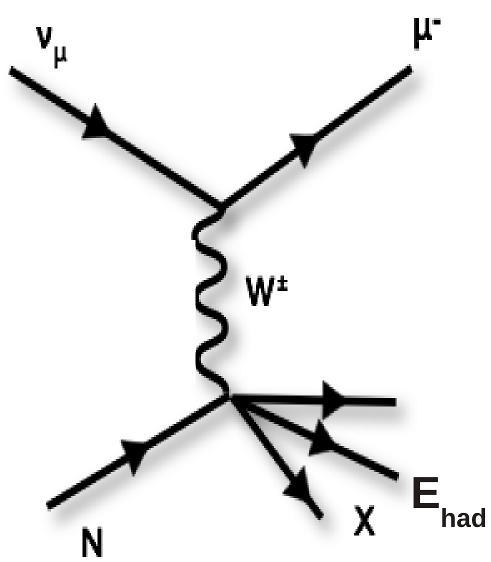
15 November 2019

Introduction

- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely

$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_\nu})$$

- Neutrino energy reconstruction is obtained using the final state particles of neutrino-nucleus interactions
  - Fully active experiments reconstruct the energy using: $E_\nu = E_{lepton} + hadron$



- Nuclear effects modify the kinematics of the particles and the reconstruction of the neutrino energy

Neutrino Scattering

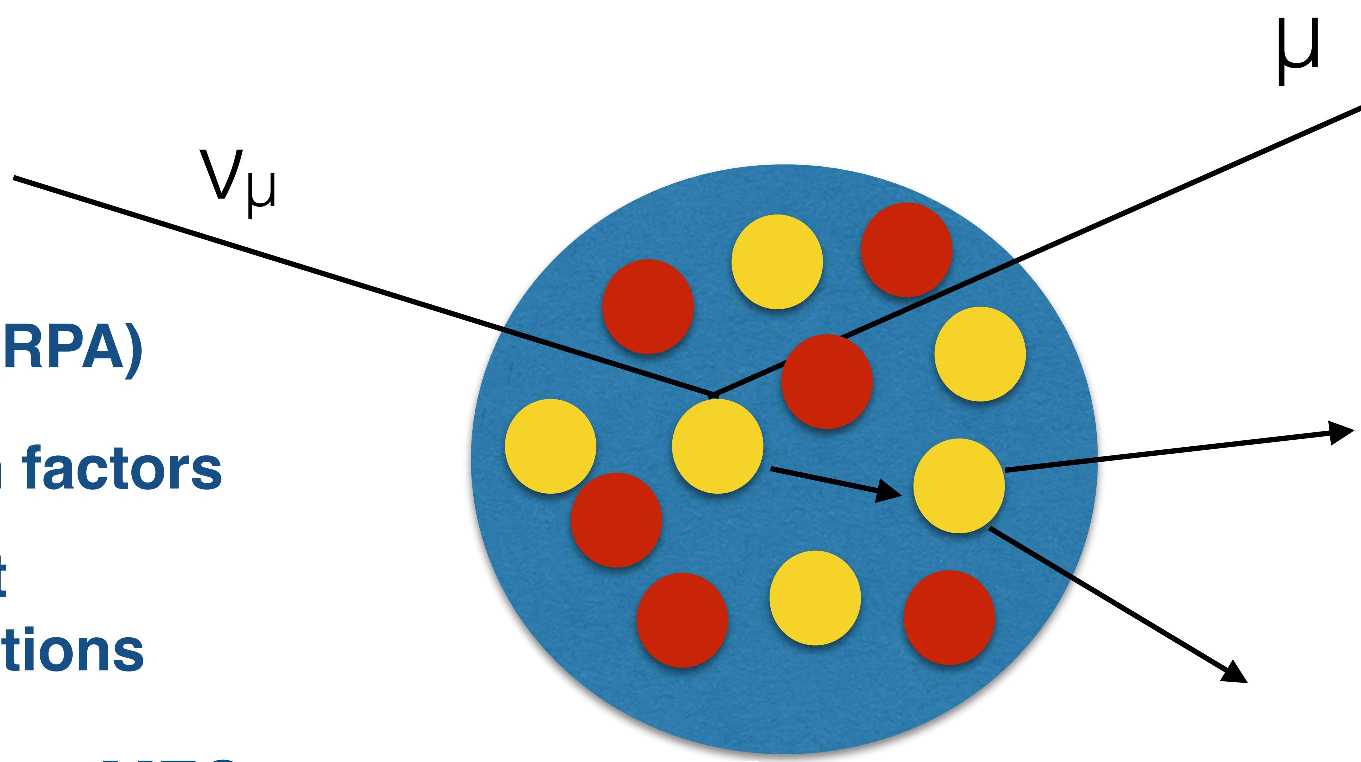
- Understanding neutrino interactions is challenging
- Modeling the interactions and measuring them present different types of challenges

Nuclear long range correlations (RPA)

Nucleon form factors

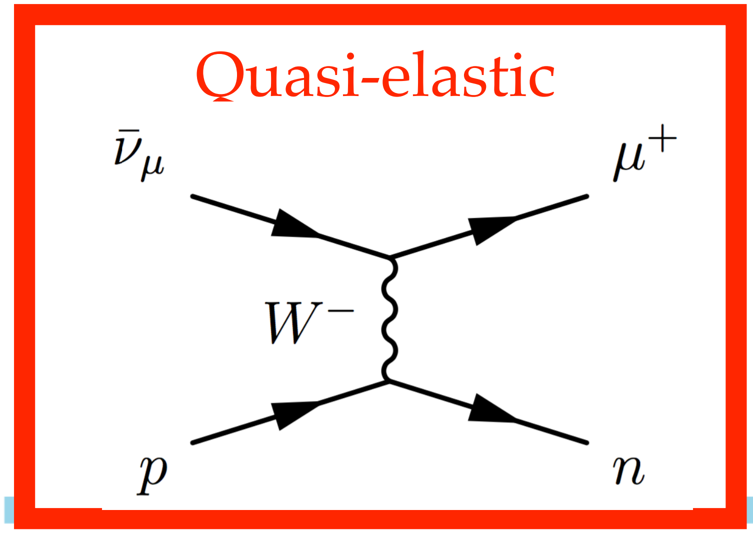
Nuclear short range correlations

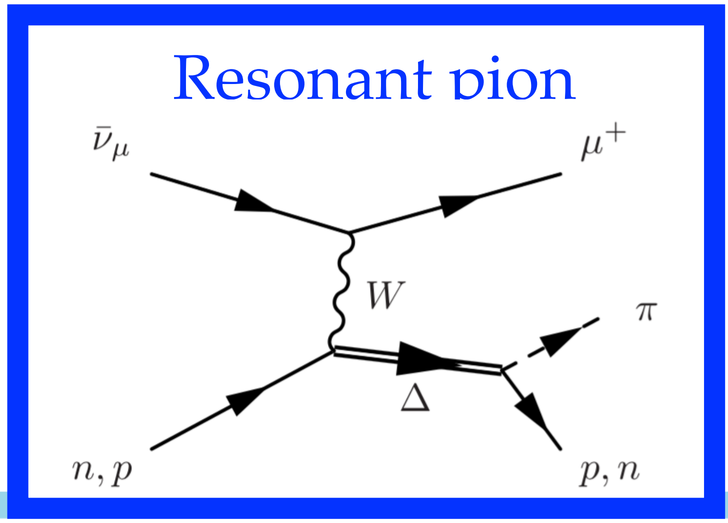
2p2h describes MEC

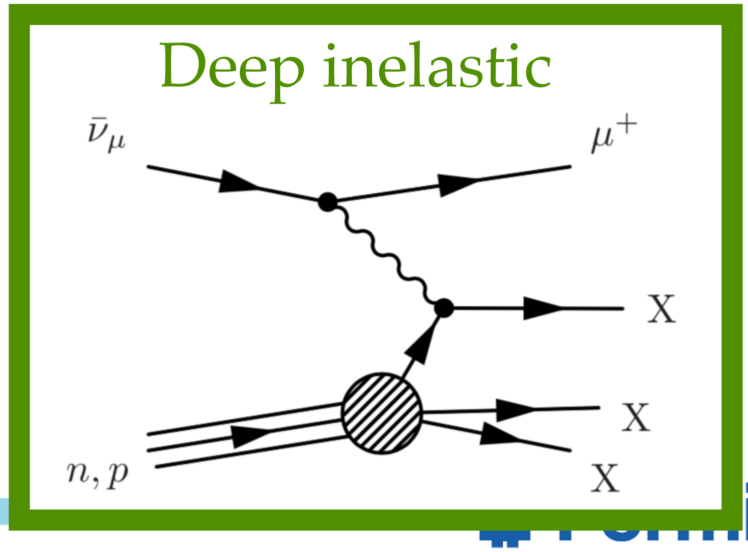


Fermi motion
Pauli blocking
Removal Energy

Final State Interactions

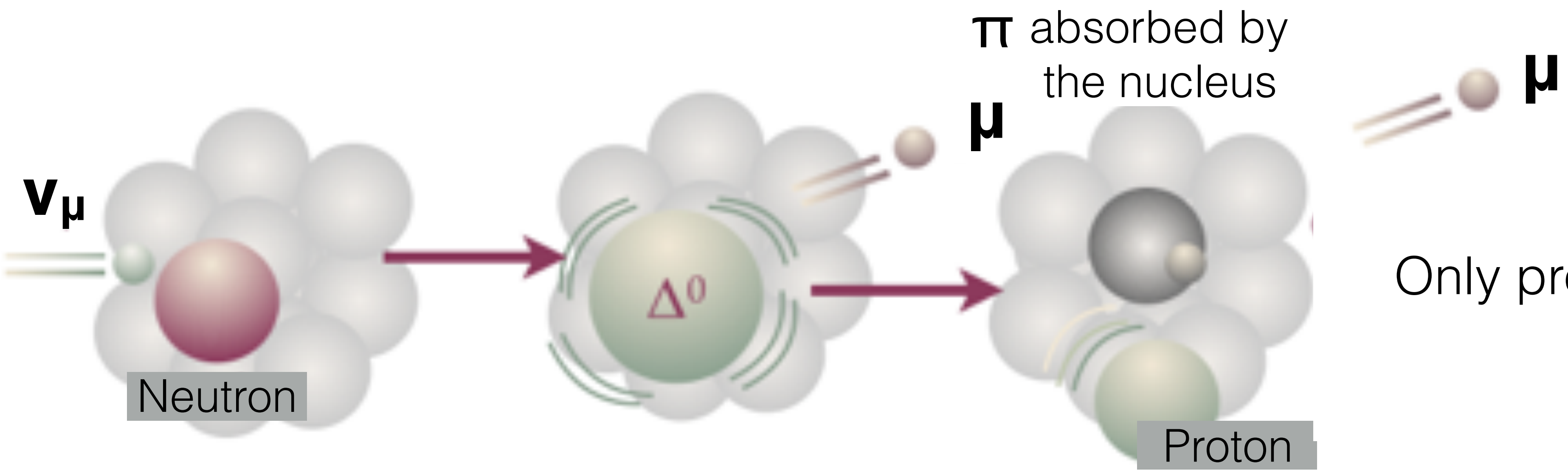






Example of Nuclear Effects (Final State Interactions)

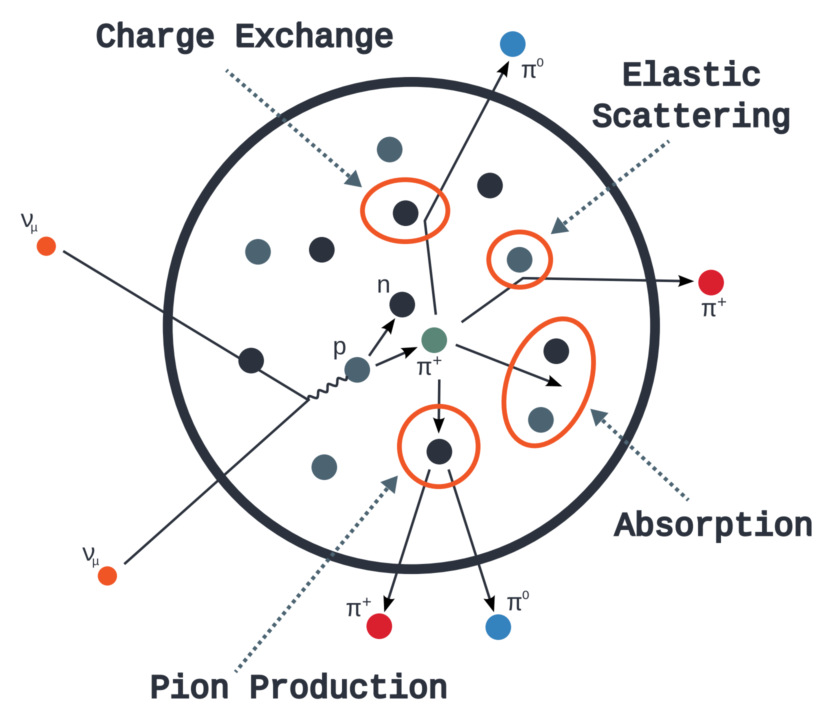
- Final state interactions (FSI):
  - Due to final state interactions, particles can interact with nucleons, pions can be absorbed before exiting the nucleus, and other nucleons get knocked out



Only proton and muon escape

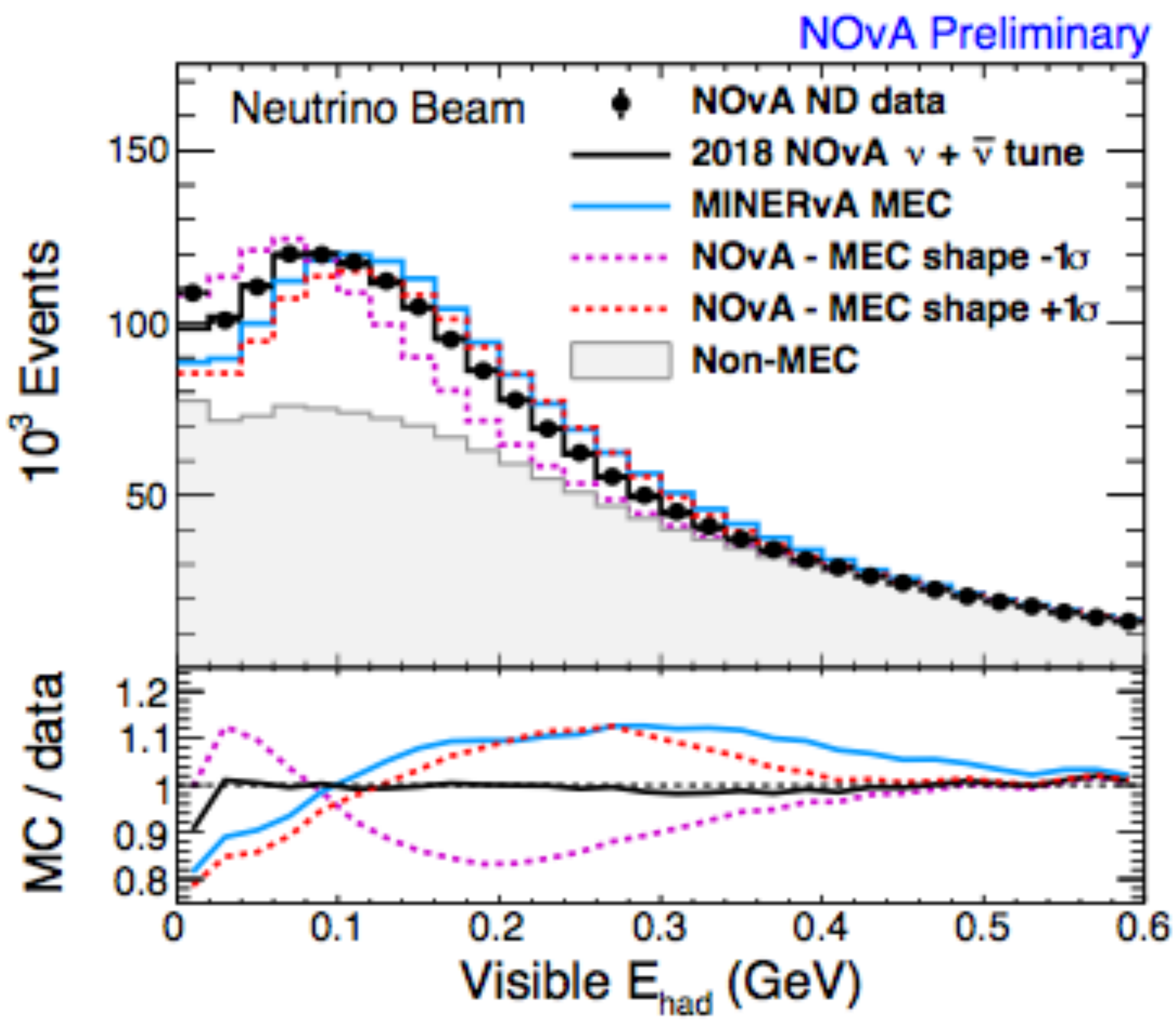
Start as a RES interaction, the pion is absorbed and the interaction looks QE like in our detector

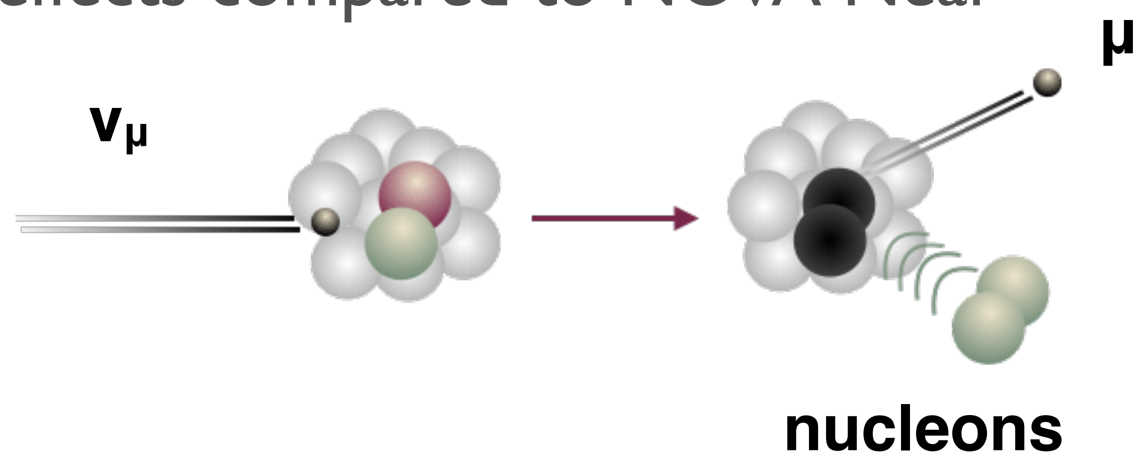
- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics!



Detailed Understanding of Neutrino Interactions is Critical for Oscillation Experiments

•Example of different models for multi-nucleon effects compared to NOvA Near Detector data





The most important systematics

- Neutrino cross sections
  - Particularly nuclear effects (RPA and MEC)
- Neutron uncertainty

Fermilab Wine and Cheese Seminar, June 15 2018, Alex Himmel

MINERvA MEC: Theoretical prediction from Valencia Model PRC 70, 055503 (2004) tuned with **MINERvA** data

NOvA MEC: GENIE Empirical MEC tuned with NOvA ND data

Source of uncertainty for oscillation experiment

NOvA

Source of uncertainty	ν_e signal (%)	Total beam background (%)
Cross sections and FSI	7.7	8.6
Normalization	3.5	3.4
Calibration	3.2	4.3
Detector response	0.67	2.8
Neutrino flux	0.63	0.43
ν_e extrapolation	0.36	1.2
Total systematic uncertainty	9.2	11
Statistical uncertainty	15	22
Total uncertainty	18	25

Phys. Rev. D 91.072010

T2K

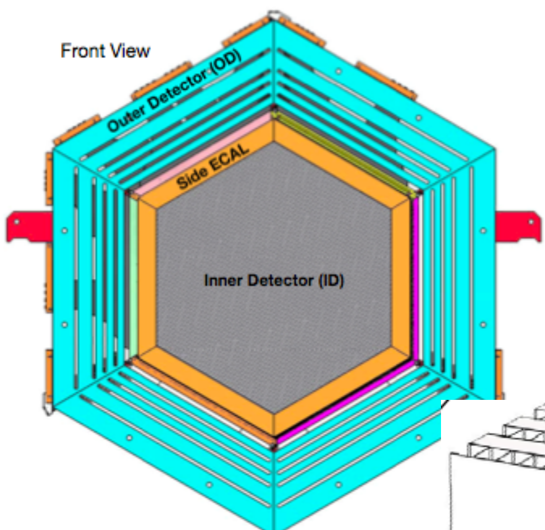
Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

Phys. Rev. D 98.032012

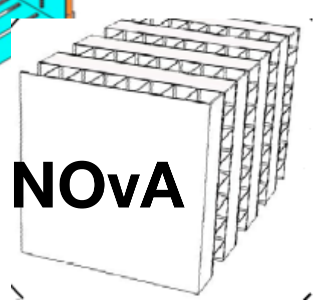
Present and Future

- We are using heavy targets for oscillation experiments, such as carbon and liquid argon
- The field of oscillation experiments are getting more statistics: accelerators are doing better than ever, and detectors are getting bigger

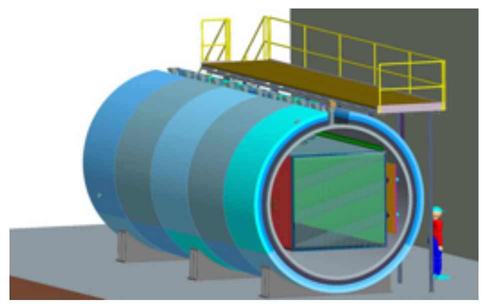
MINERvA



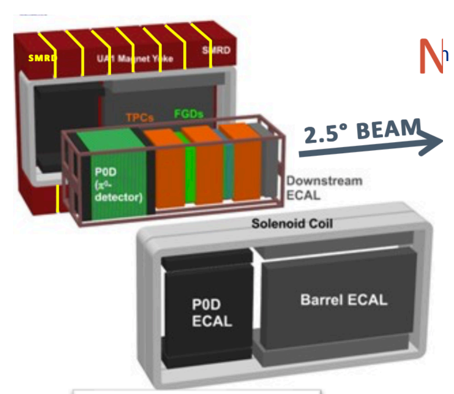
NOvA



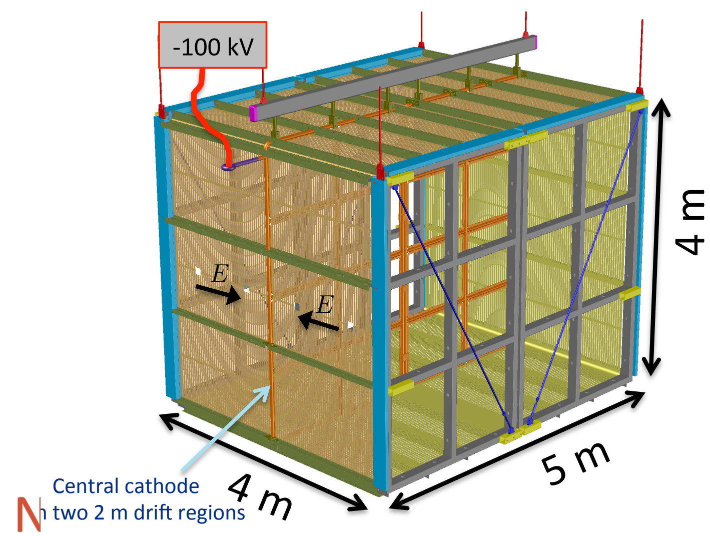
MicroBooNE



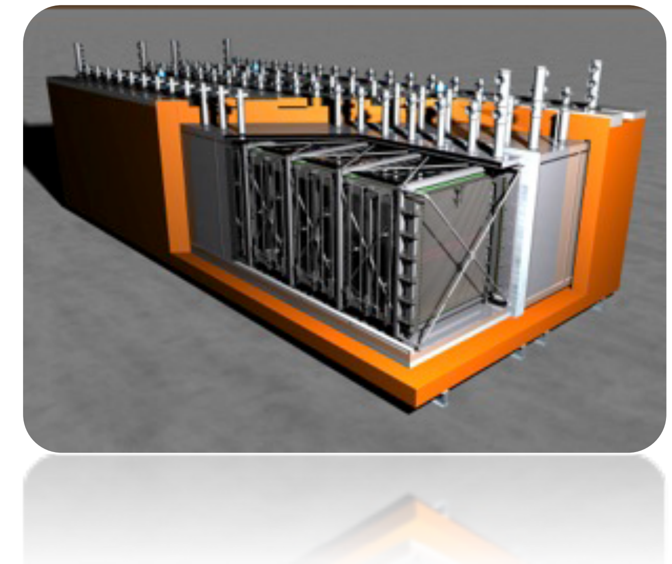
T2K



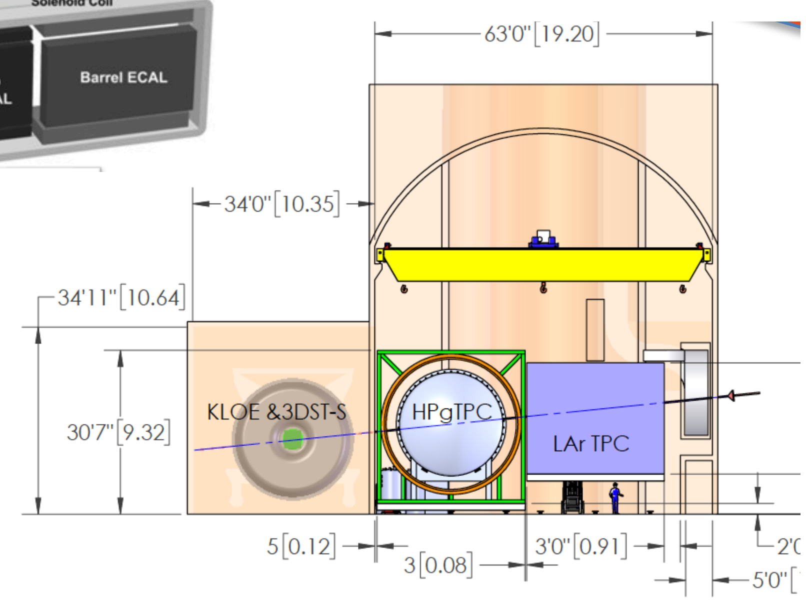
SBND

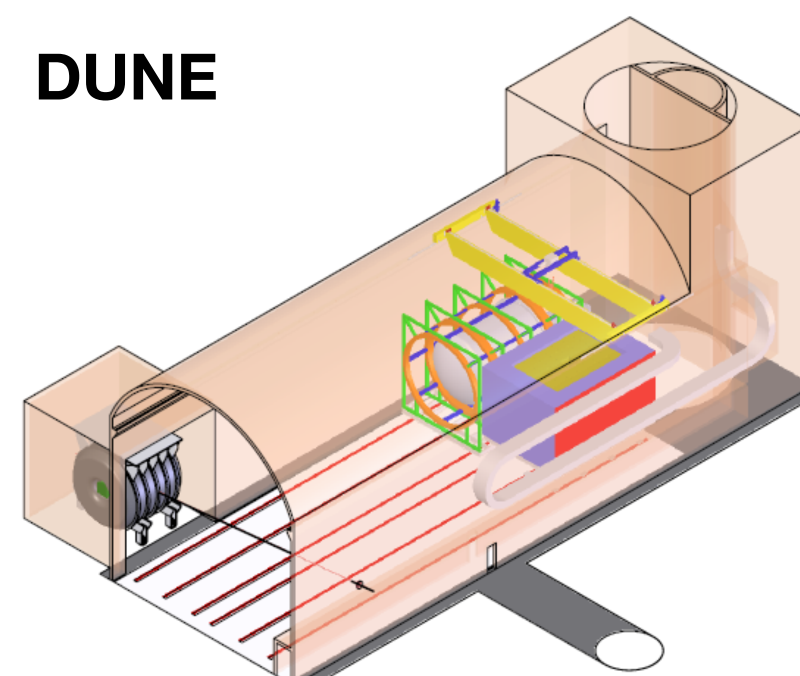


ICARUS



DUNE

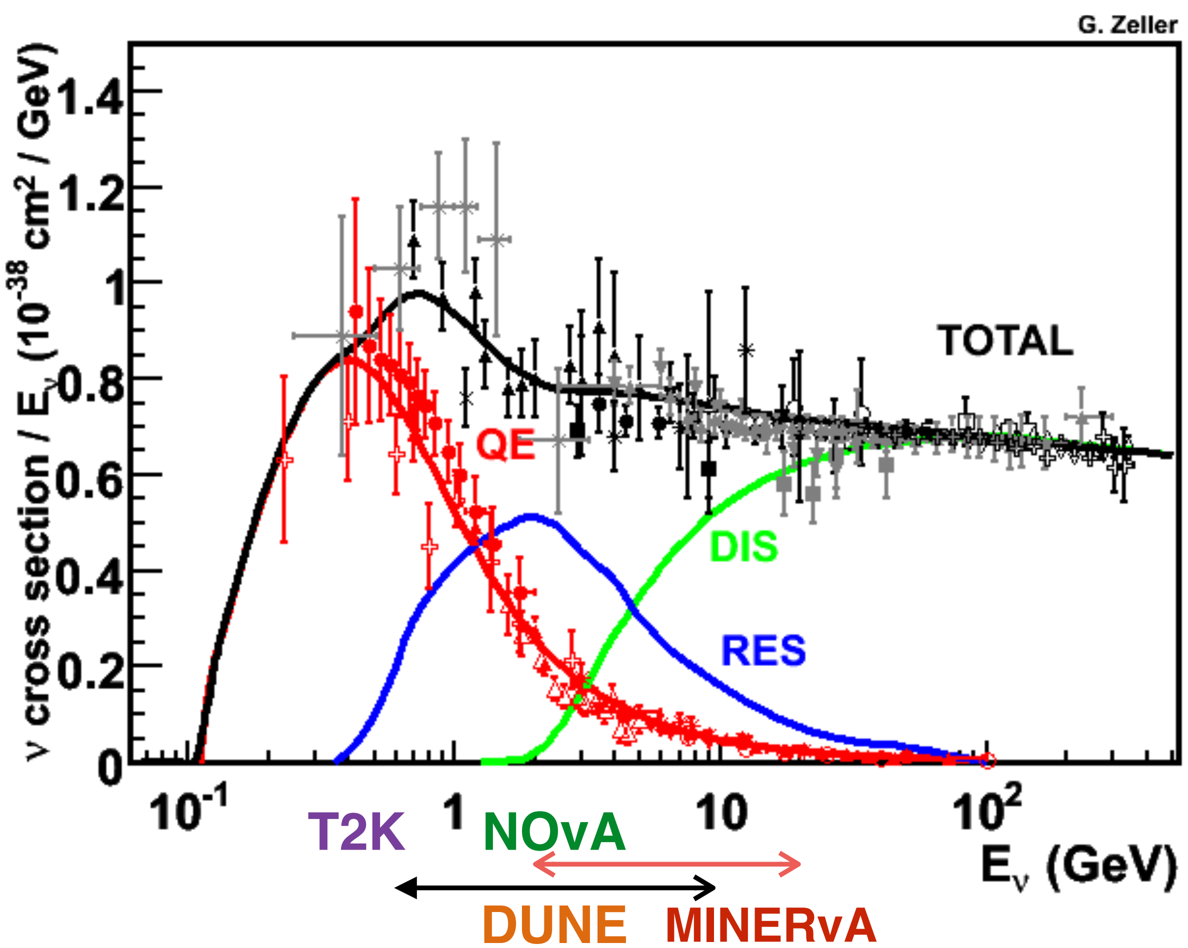




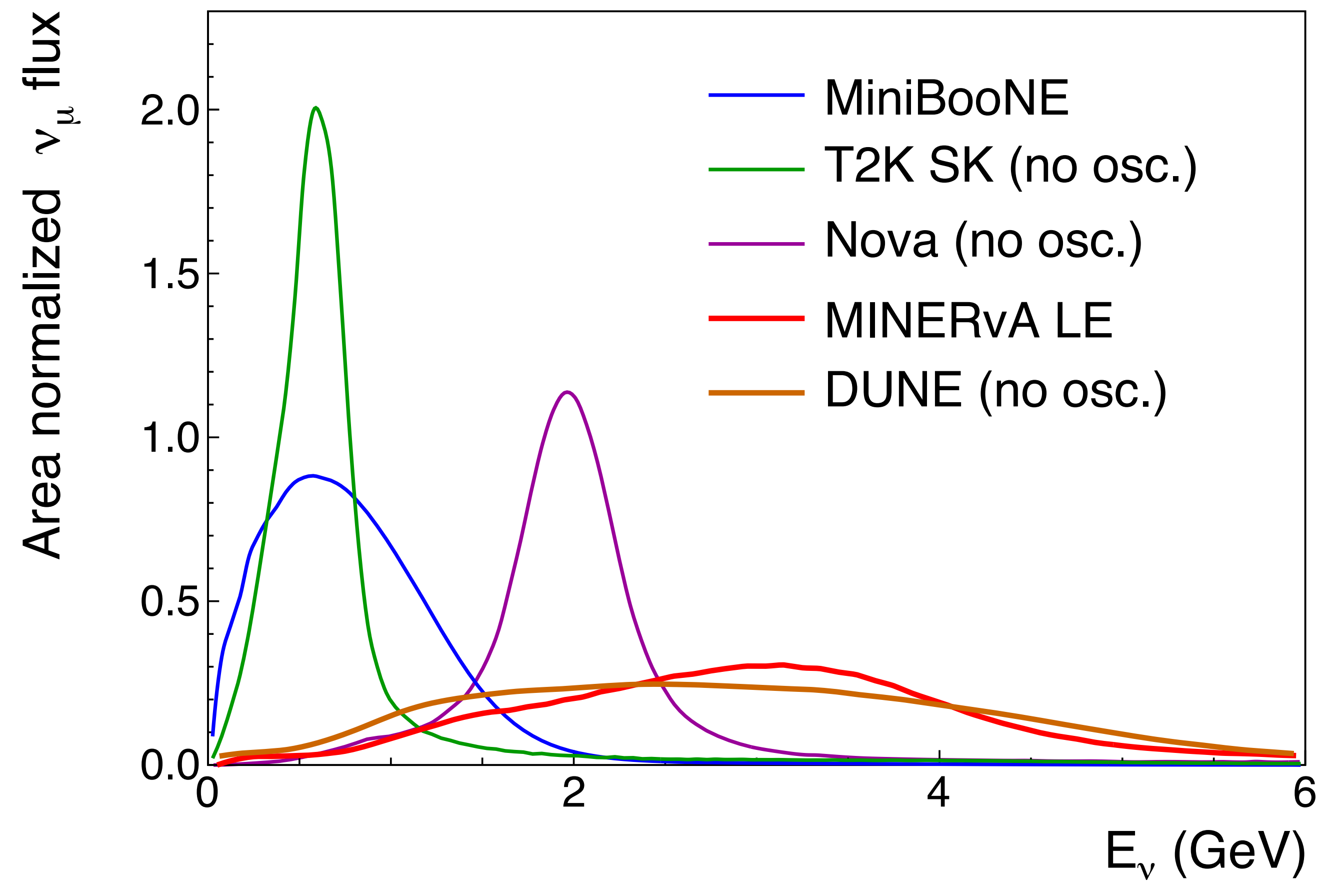
DUNE Near Detector
Complex detector, main components:
Liquid argon+downstream tracker
with gaseous argon target

Detectors can move to off-axis fluxes

Neutrino Energies for Different Experiments



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

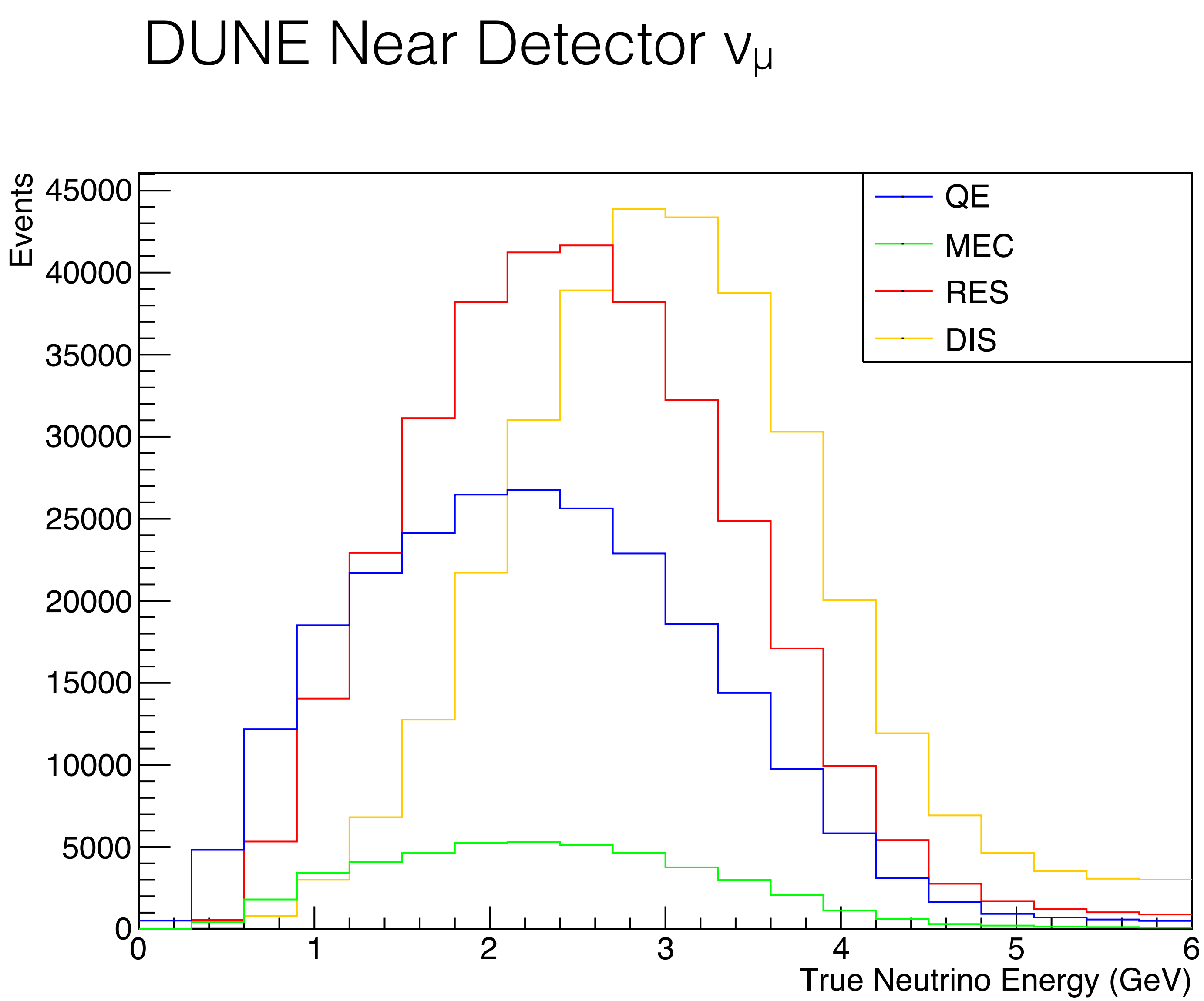


Plot courtesy of Phil Rodrigues

- We have a lot of progress these past years for the simplest interactions CCQE (0π)
- Starting to focus on the pion production, mainly because NOvA has a good contribution from pion events and T2K is including pions events in their signal to get more statistics
- Next crucial channel is the DIS scattering, the largest contribution for DUNE
- Showing results from the last few years

Muon Neutrino at the Near Detector in DUNE

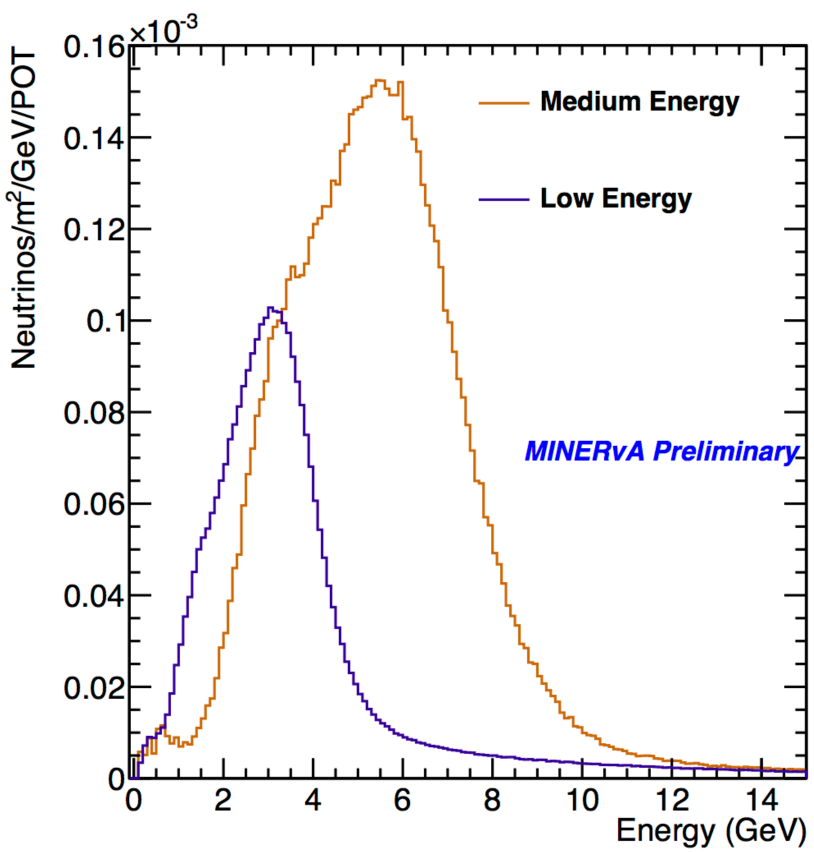
GENIE predictions for argon

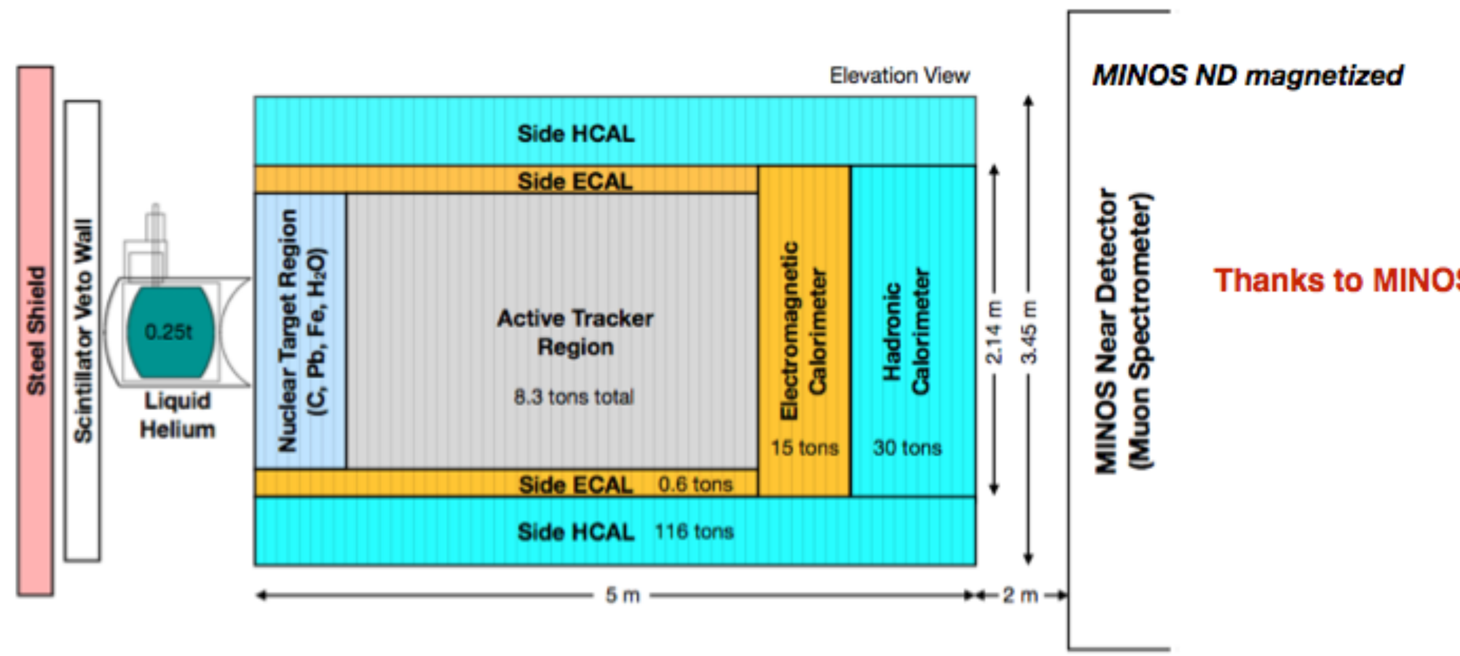


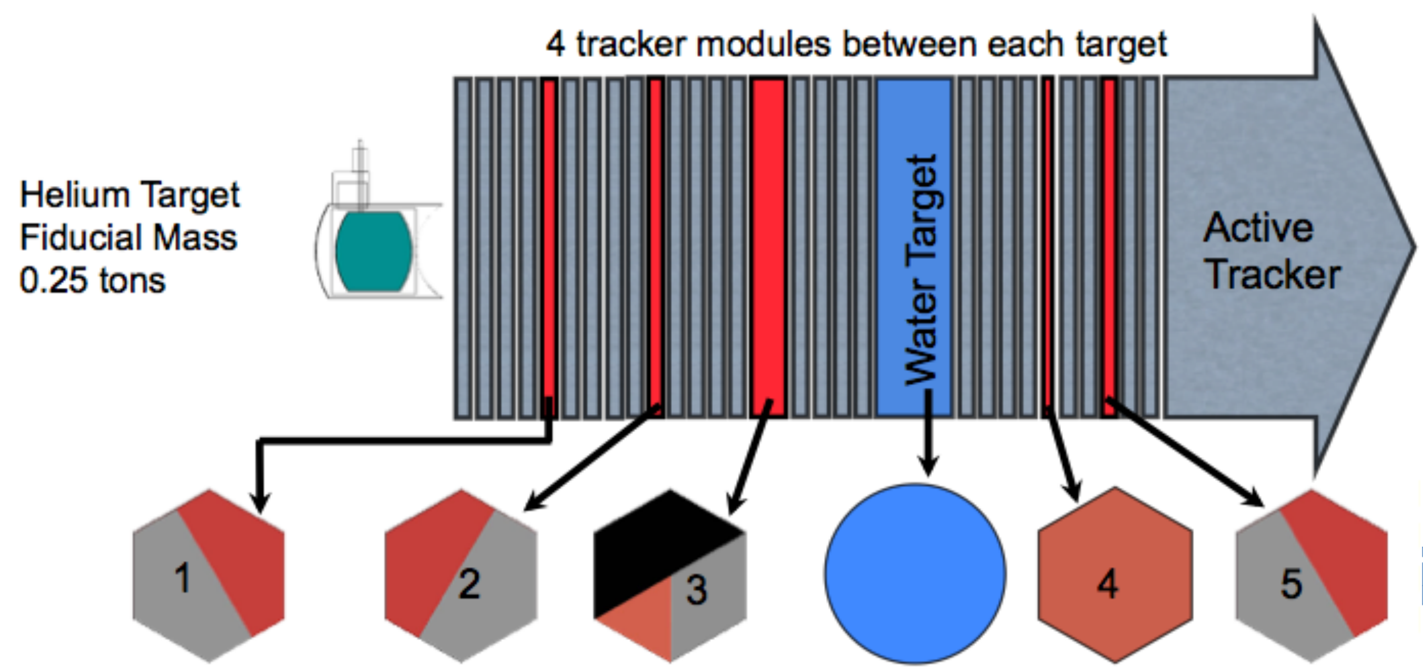
- Significant contributions from RES and DIS interactions

MINERvA Experiment

- Fine-grained scintillator tracker surrounded by calorimeters
- We have different nuclear targets which allows us to study nuclear effects and see how the different processes are affected by the nucleus







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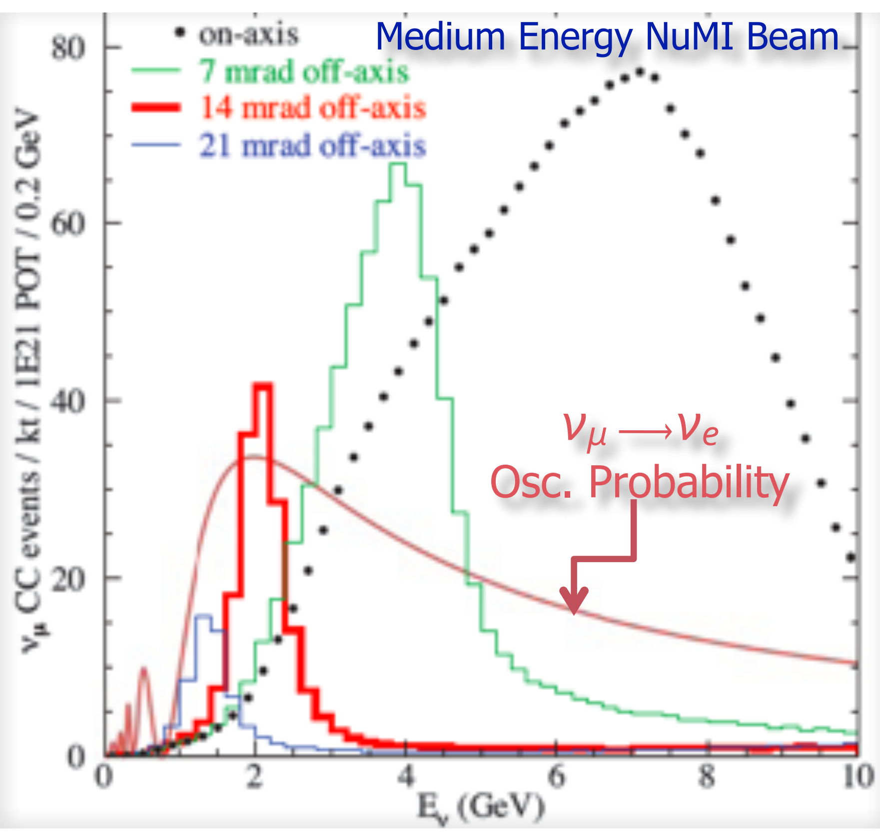
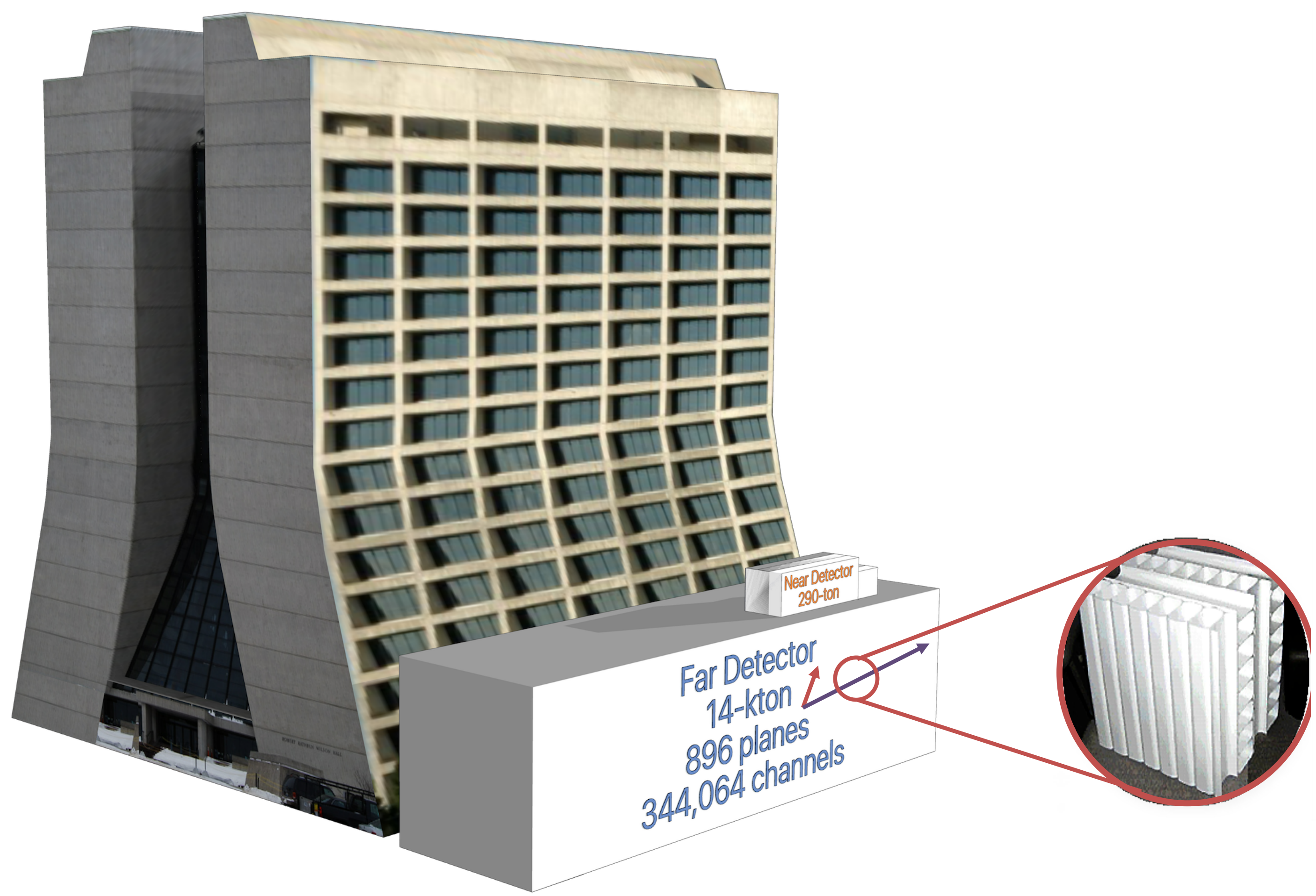
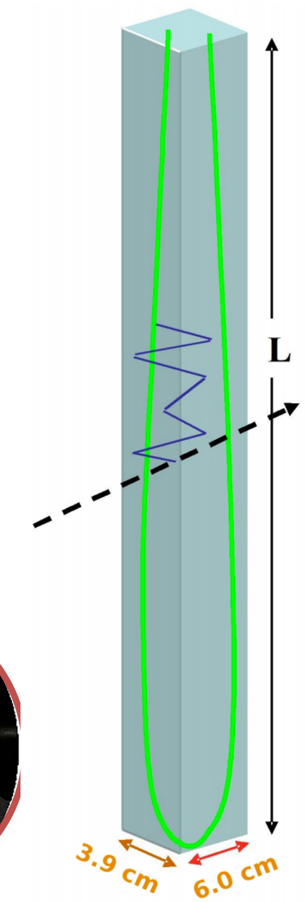
NOvA Experiment

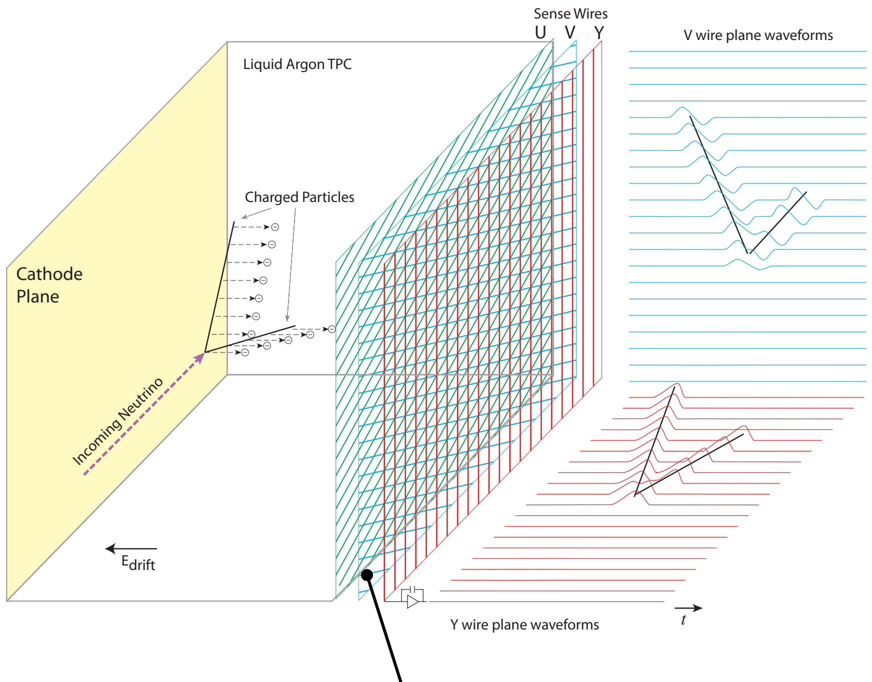
- Near Detector is 290 tons placed 300 ft underground at Fermilab
- Consists of plastic cells filled with liquid scintillator
- Off axis beam neutrinos



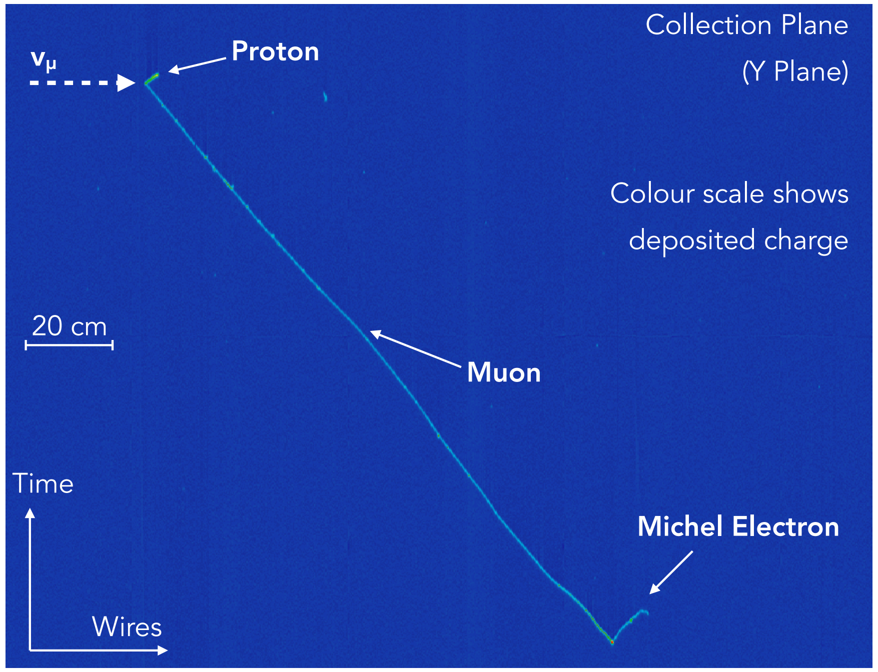


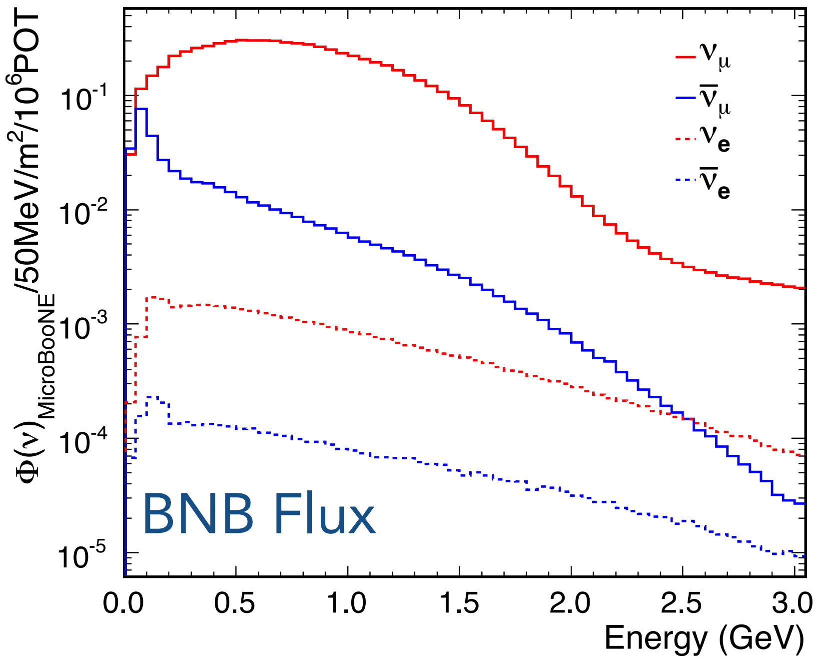


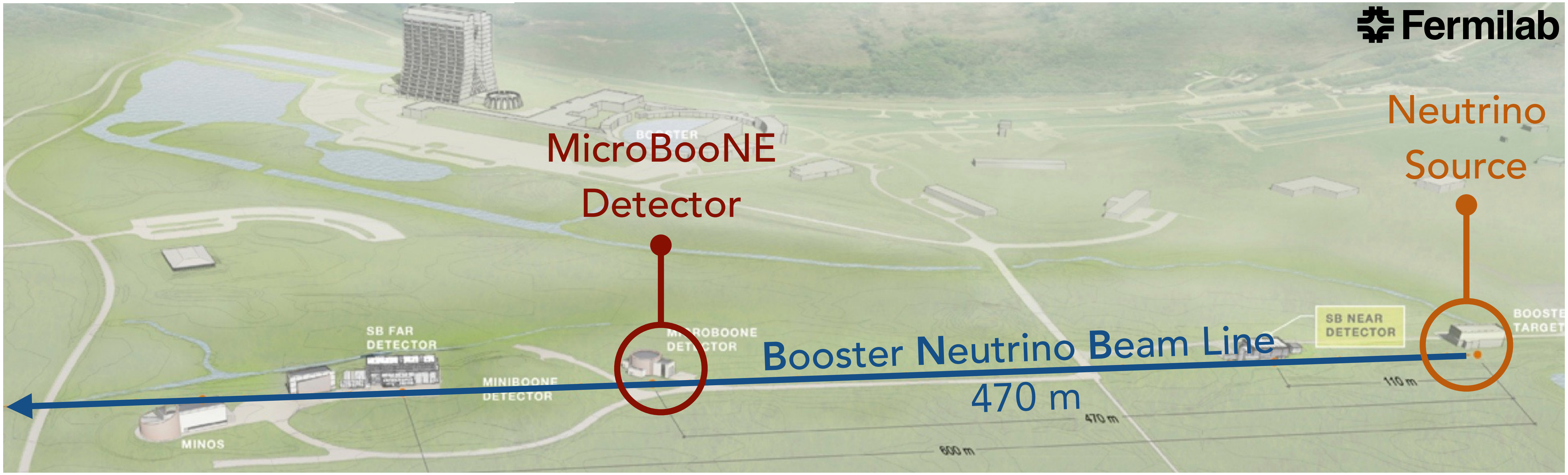
MicroBooNE Experiment



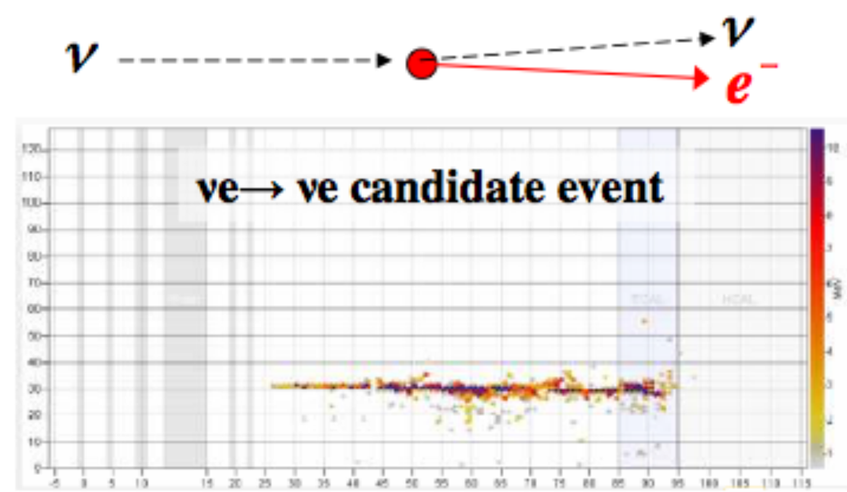
8192 wires (3 mm pitch)





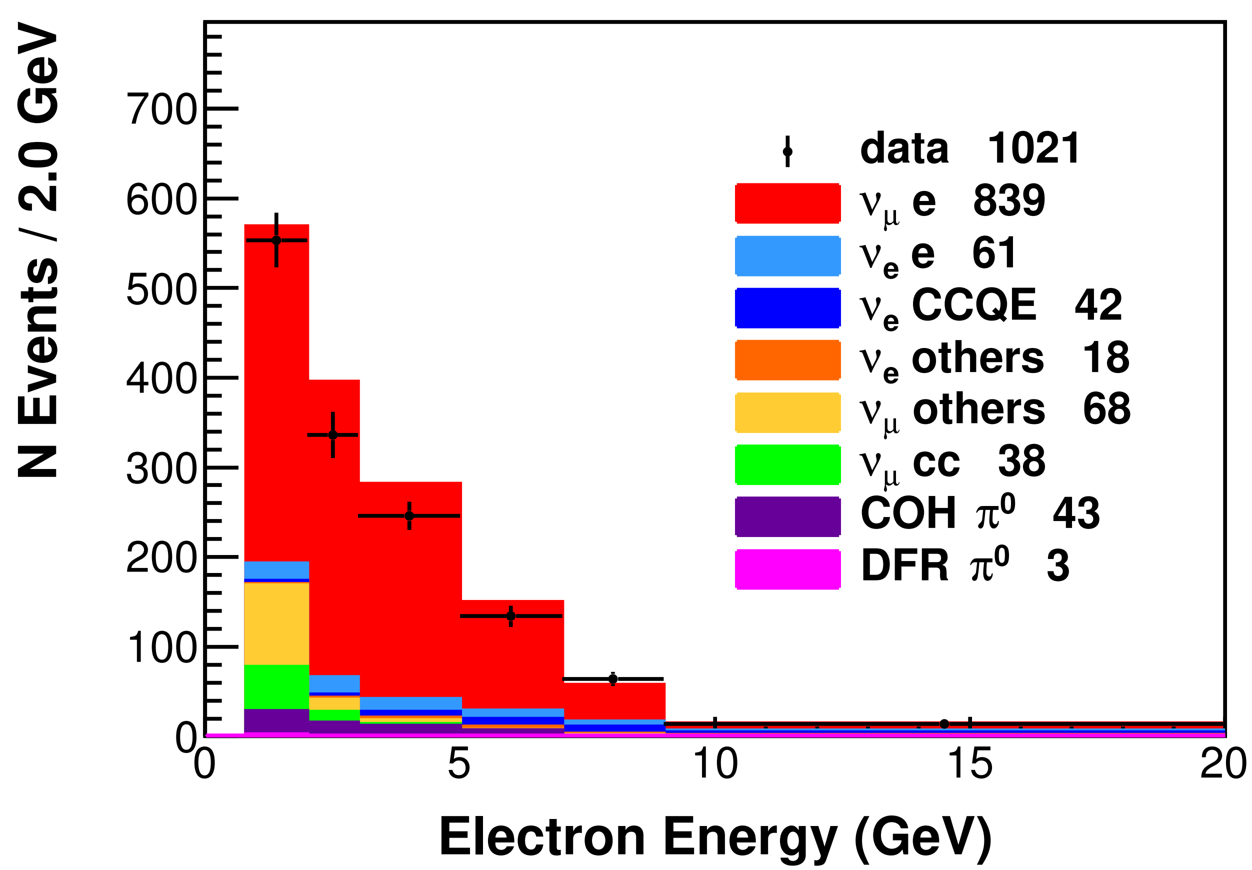


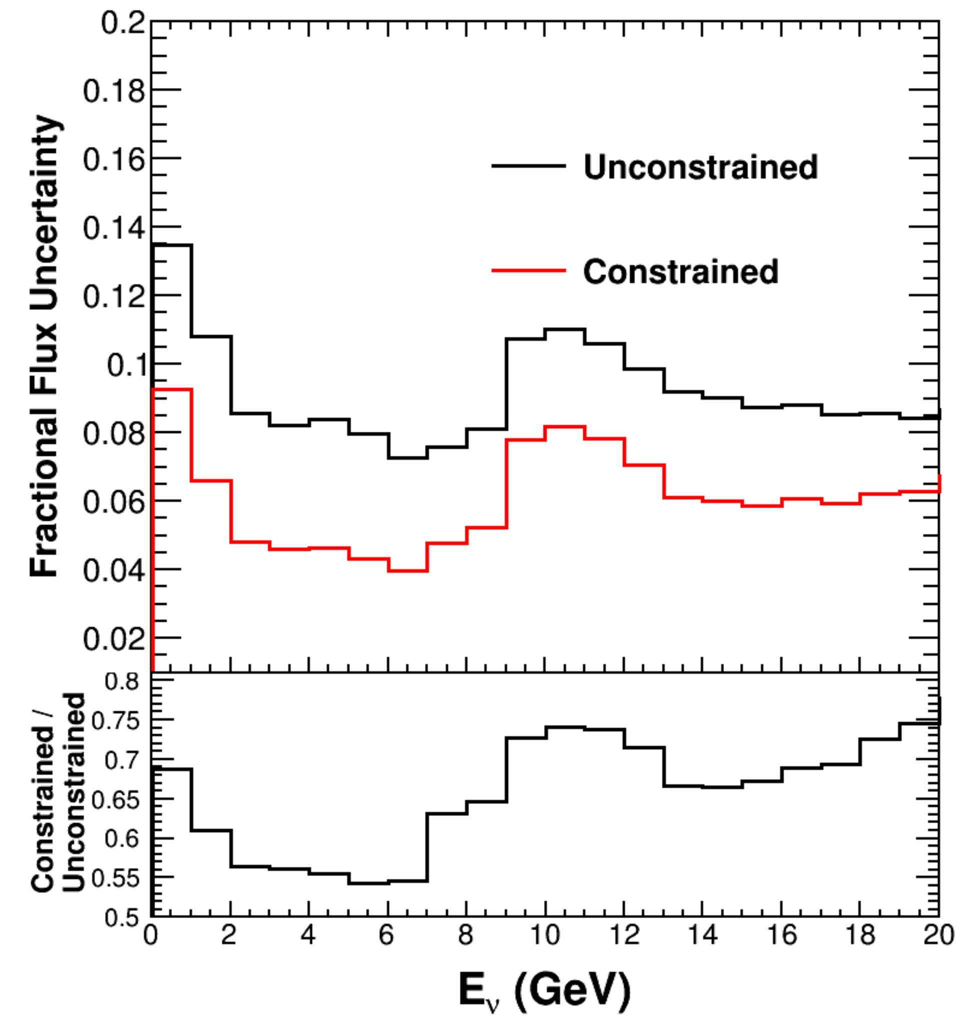
Flux Prediction



- MINERvA constrain flux with in-situ measurements: ν+e scattering
- Using a total sample of 810 signal events
- The measurement reduces the normalization uncertainty on the ν_μ NuMI flux from 7.5% to 3.9%
- The most precise flux constraint ever

arXiv:1906.00111





Neutrino Event Generators

- We have several event generators: GENIE, NEUT, NuWro and GiBUU

GENIE

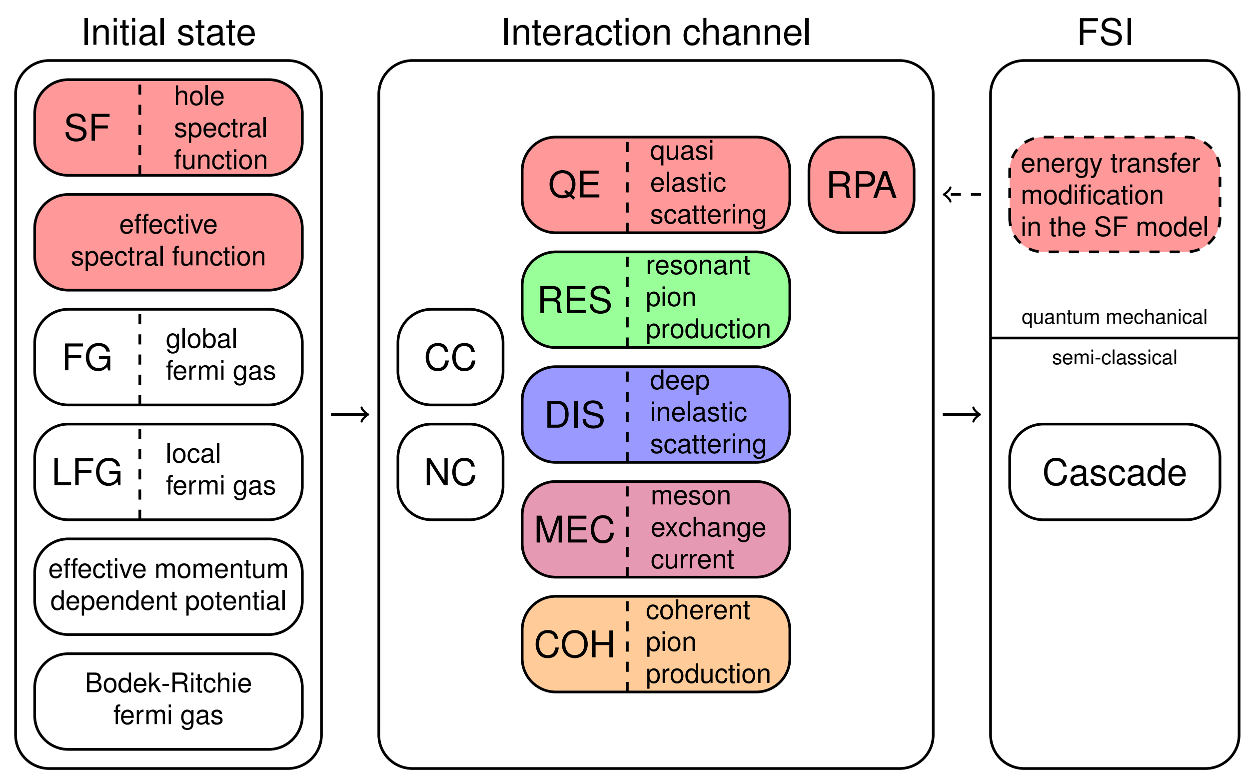
- CCQE models
  - Llewellyn Smith
  - Nieves, Amaro and Valverde
- MEC models
  - Empirical
  - Nieves Simo Vacas
- Nuclear Models
  - Relativistic Fermi Gas
  - Local Fermi Gas
  - Effective Spectral Functions

- Single Kaon
- Λ production

- RES
  - Rein-Sehgal
  - Berger-Sehgal
  - Kuzmin-Lyubushkin-Naumov
- COH
  - Rein-Sehgal
  - Berger-Sehgal
  - Alvarez Ruso
- FSI - Intranuke
  - Full Intra-Nuclear cascade
  - Schematic based on Hadron-nucleus data

Marco Roda, Nuint 2018

NuWro



Jan Sobczyk, Nuint 2018

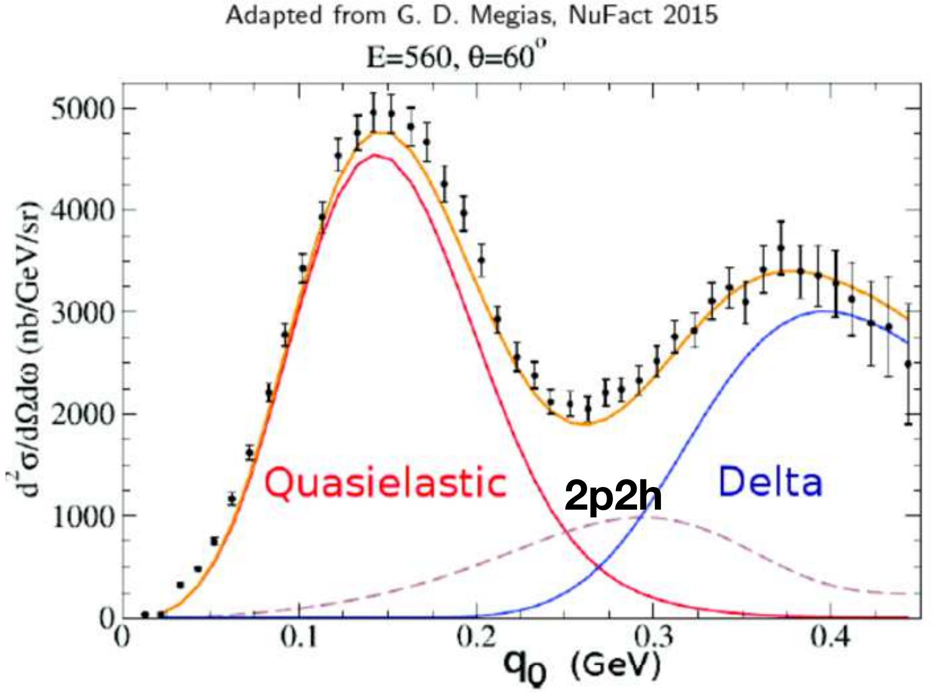
Inclusive CC Double Differential Cross Section from MINERvA

- Cross section in q_0 and q_3
  - q_0 is calorimetric hadronic energy and q_3 is the three momentum transfer

$$E_\nu = E_\mu + q_0 \qquad q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

From electron scattering

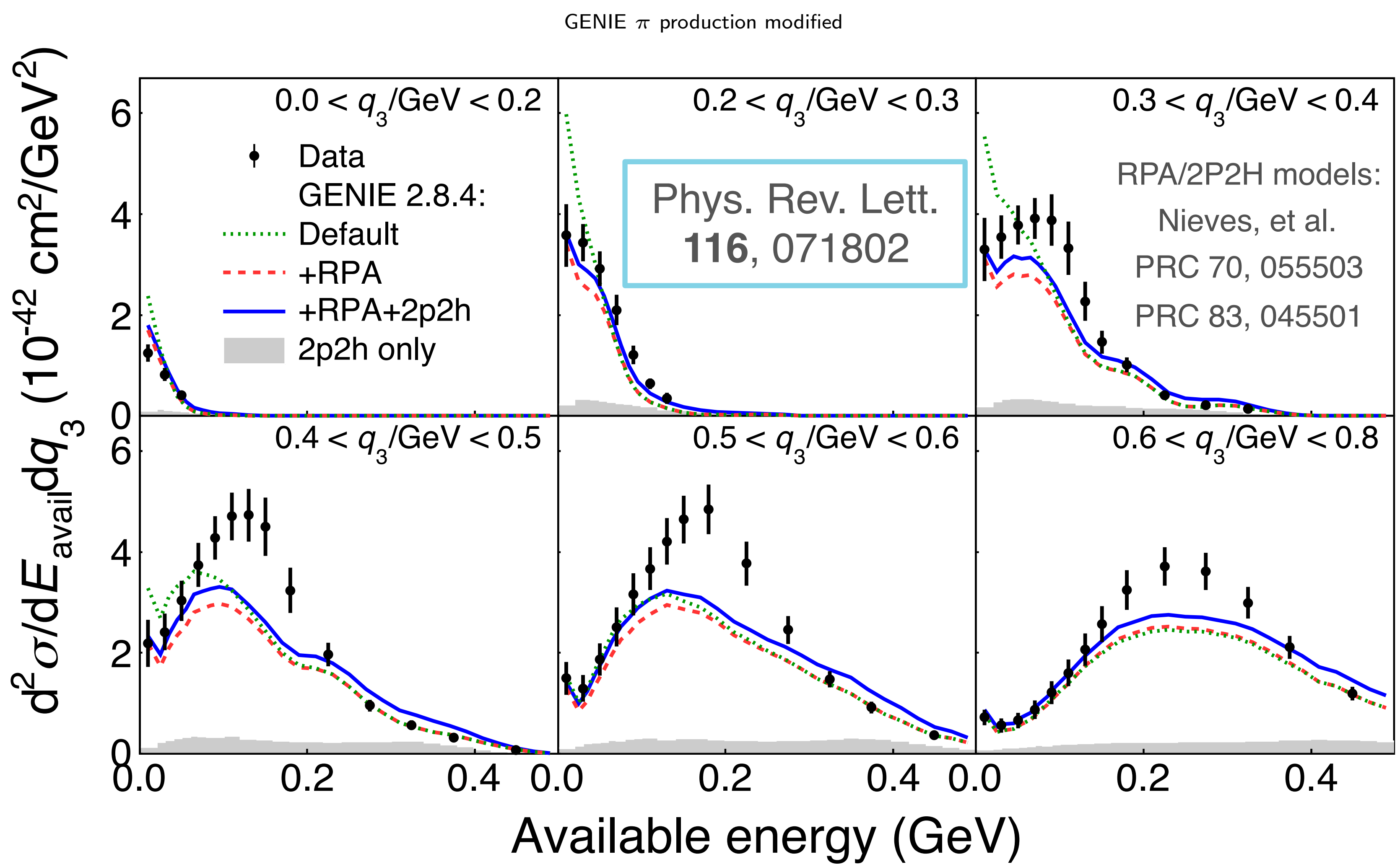
Adapted from G. D. Megias, NuFact 2015



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

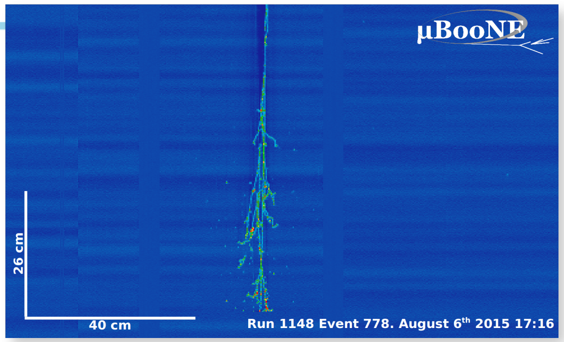
New model predictions for 2p2h and RPA from the Valencia group (PRC 70, 055503 PRC 83, 045501)

Similar measurement for neutrinos using the hadronic system and the lepton

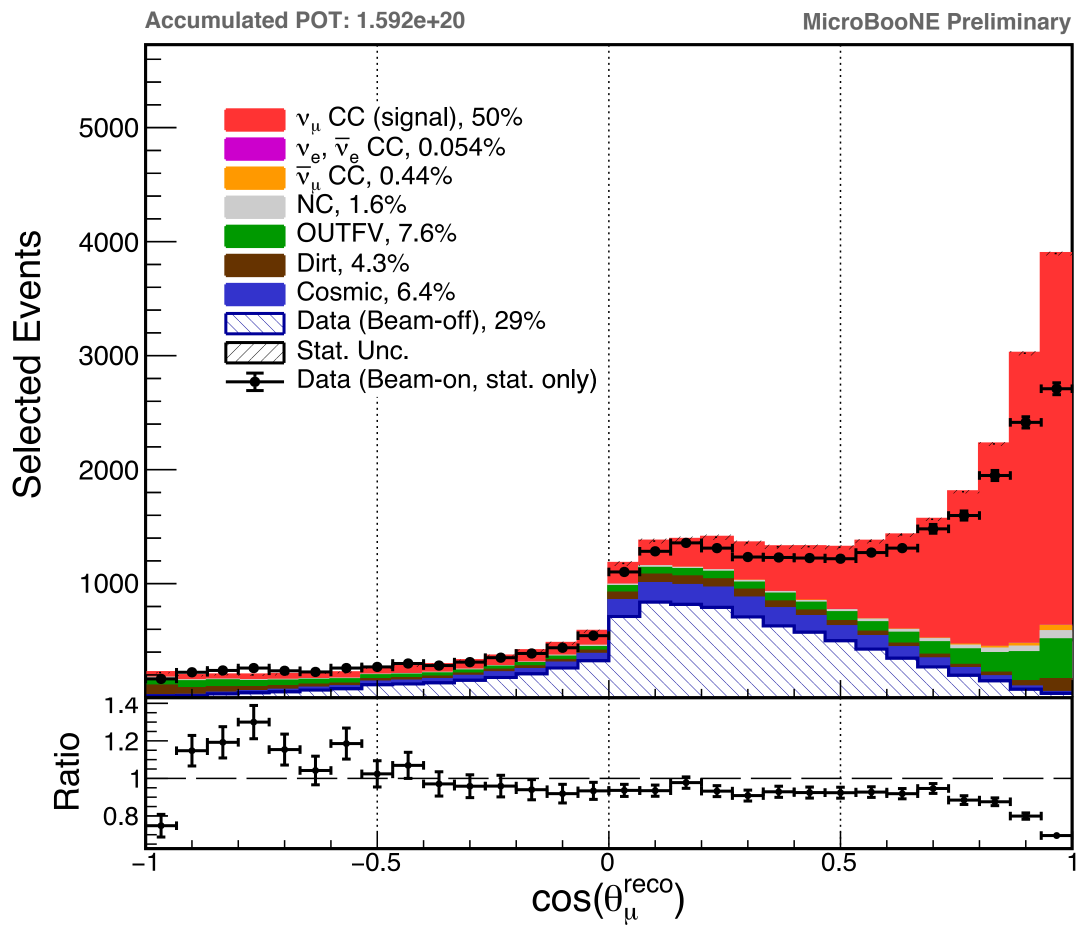


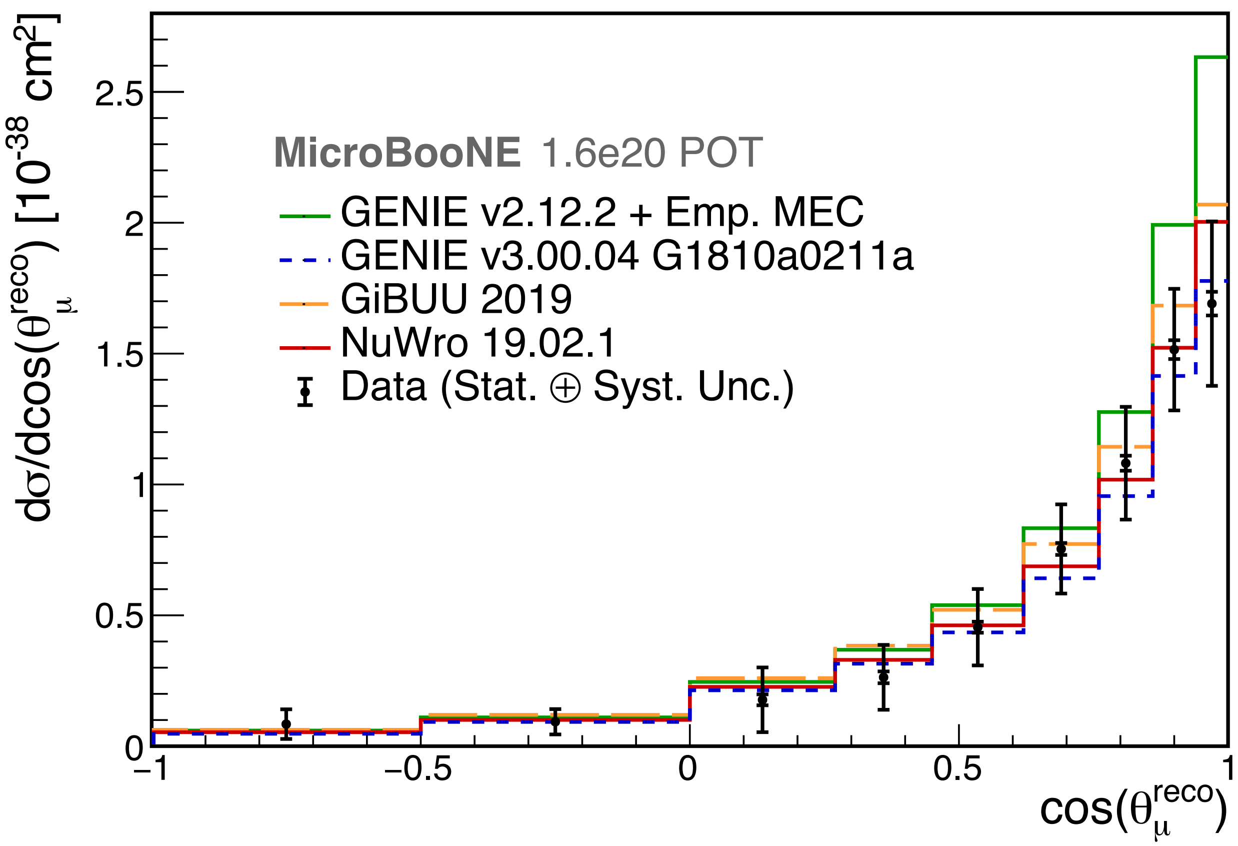
Model does not provide enough strength in some regions

First ν_μ CC Inclusive Cross Section from MicroBooNE



- MicroBooNE is on Earth's surface
- Cosmic rays are the main background
- Rate 5.5 kHz —> 25 cosmic rays per recorded event
- GENIE over predicts the cross section in the very high momentum and forward region

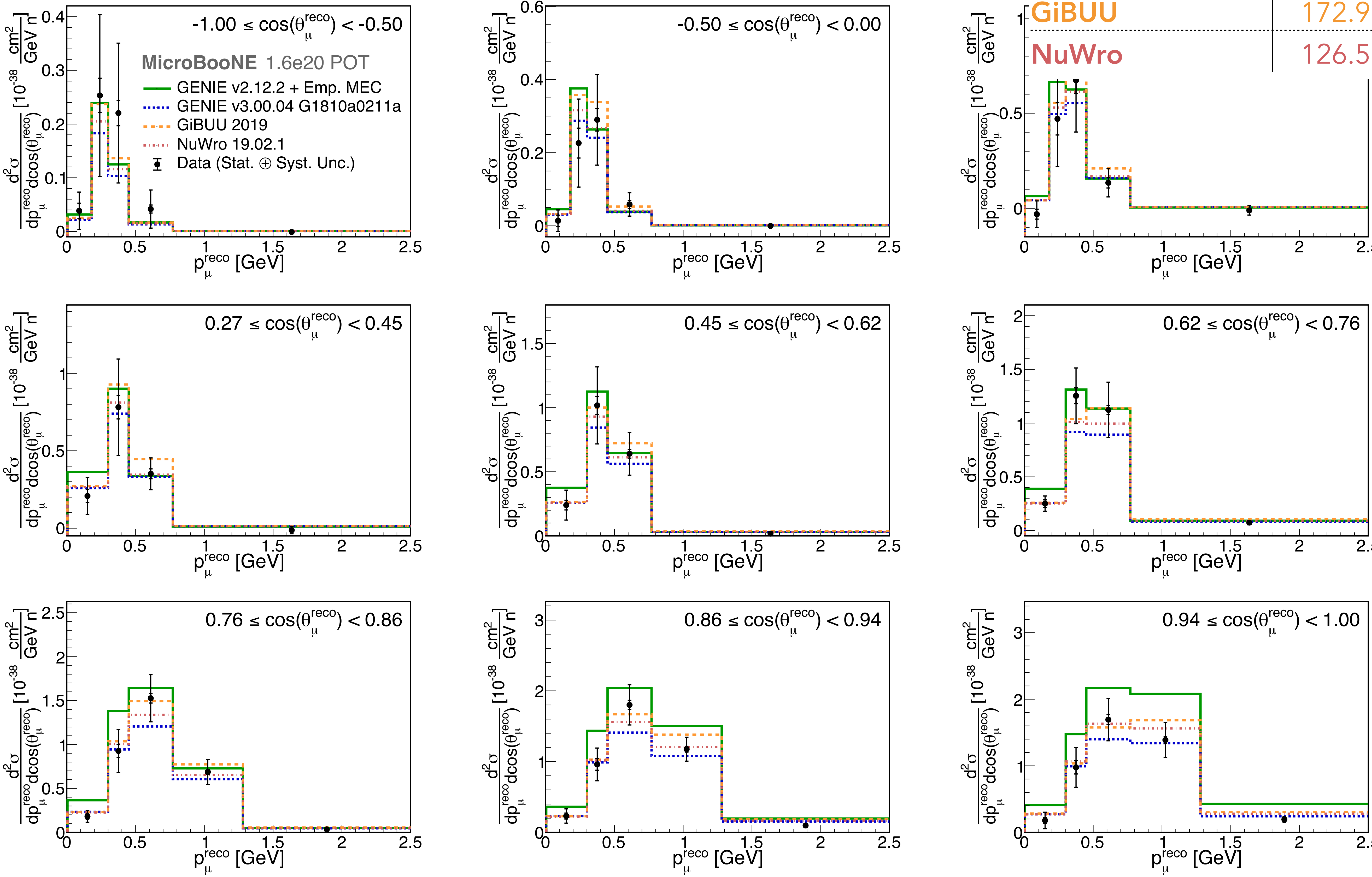




https://arxiv.org/abs/1905.09694

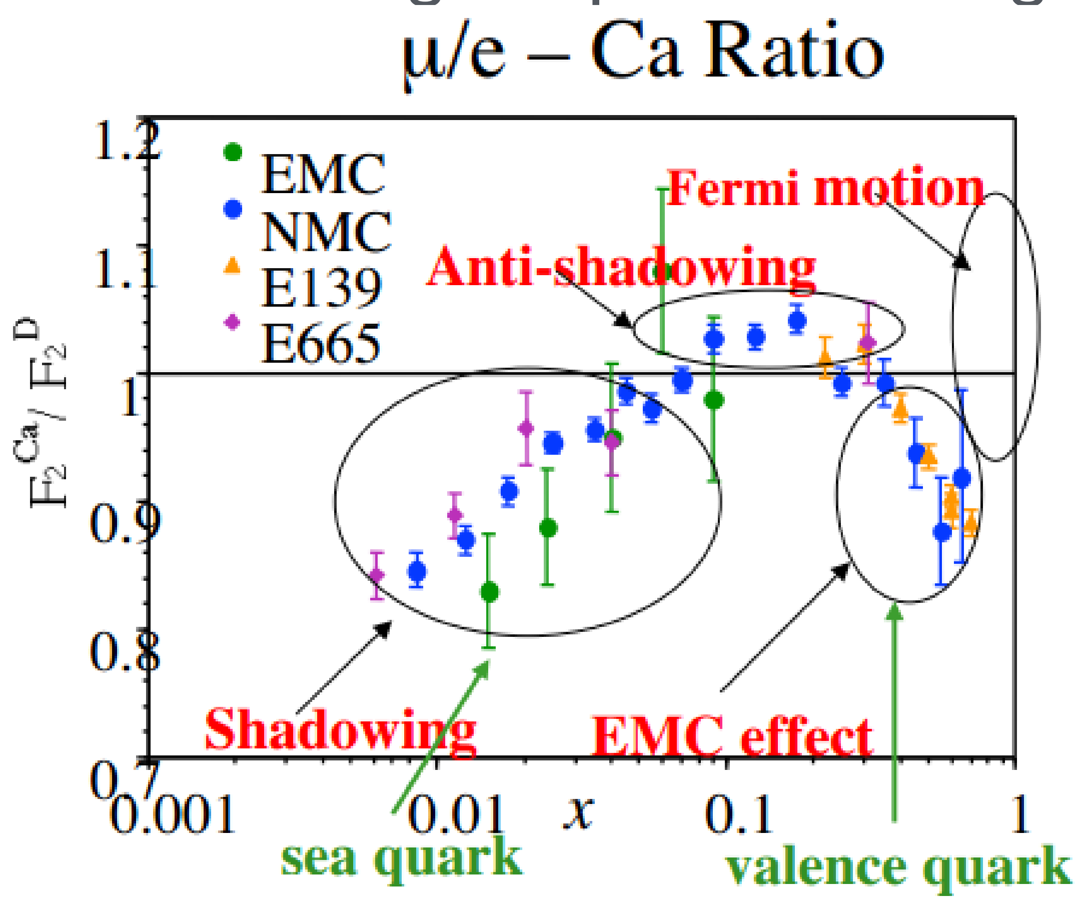
MicroBooNE Double Differential Cross Section

Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5



Deep Inelastic Scattering

- One of the most important channels for the next generation of oscillation experiment (DUNE)
- Different effects observed in charged lepton scattering



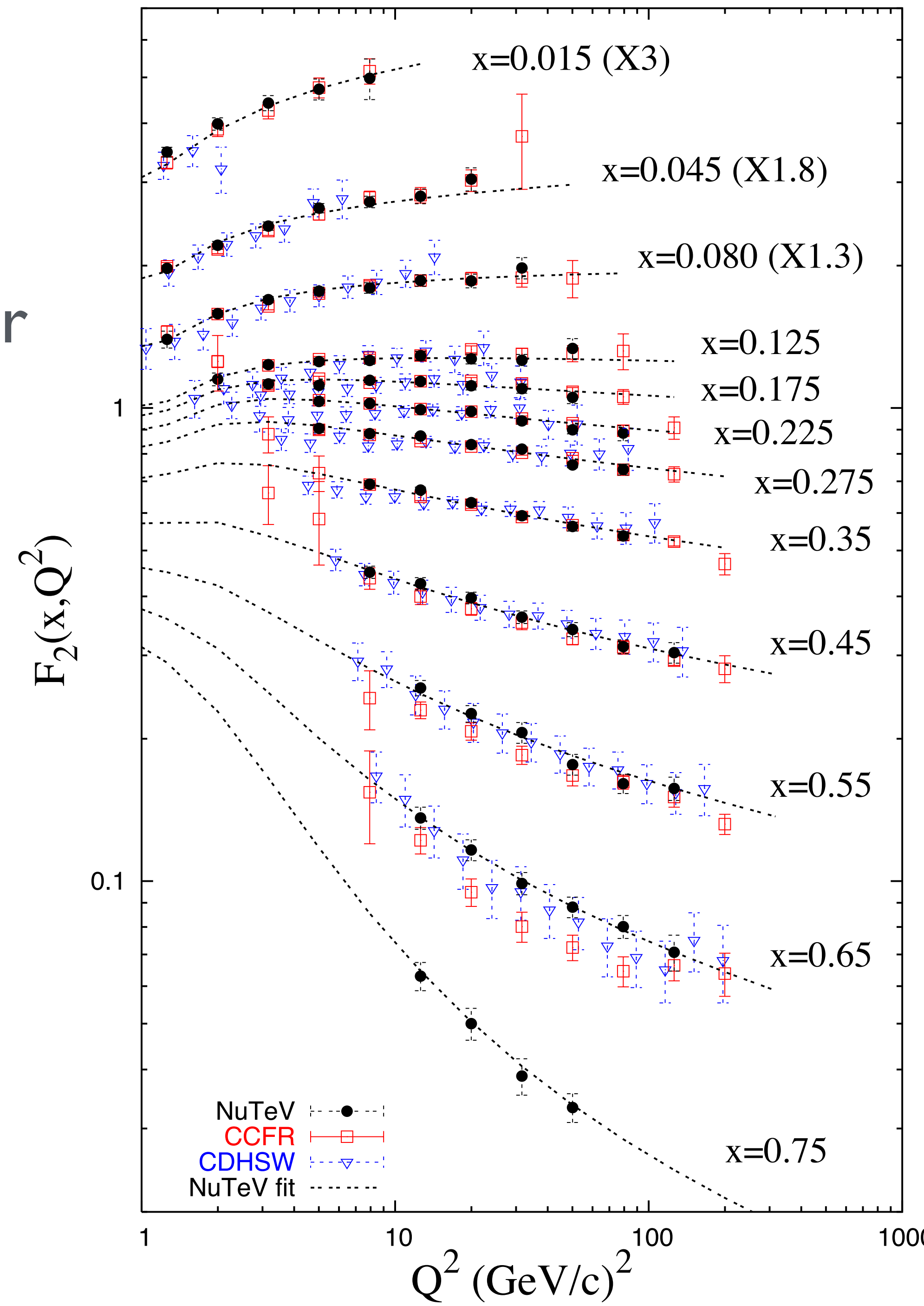
$$x = \frac{Q^2}{2ME_{had}}$$

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

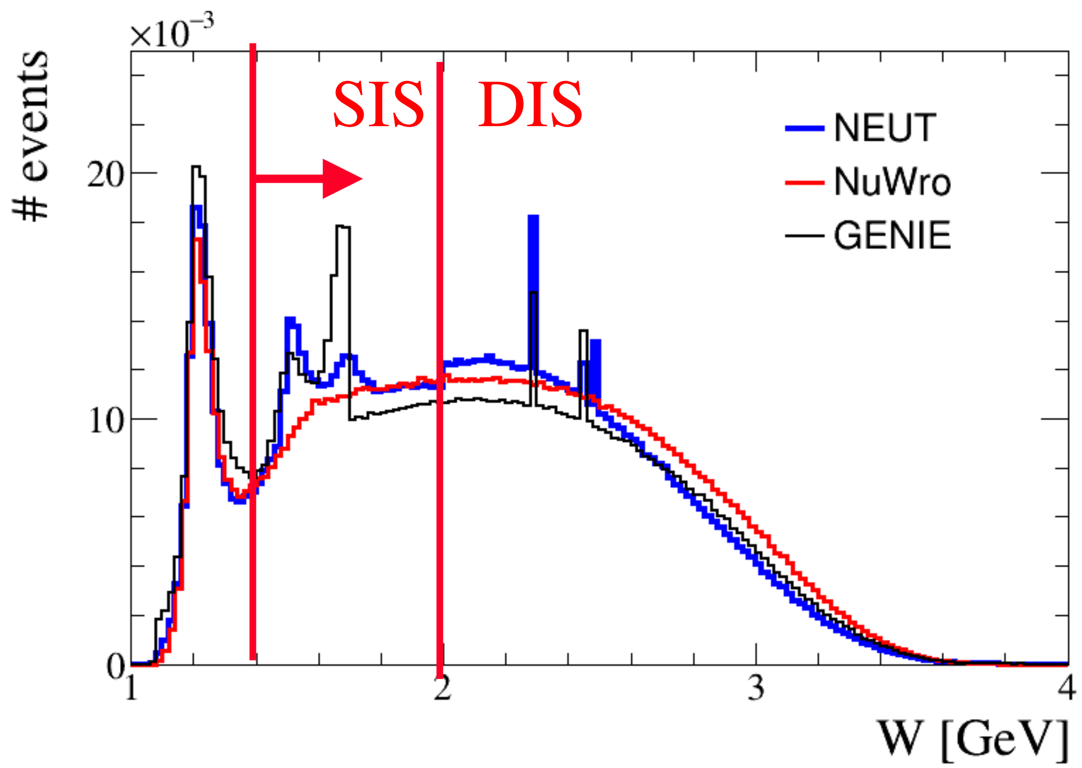
- We use x-dependent nuclear effects for Fe and Pb based on charged lepton scattering data, need to test with neutrinos

Old DIS Data

- NuTeV accumulated over 3 million neutrino / antineutrino events with 20<E<400 GeV, NuTeV operated for 15 months in 1996
- NuTeV measured F_2 on Fe
- At low x very different Q^2 dependence
- At high x (x>0.5) NuTeV is systematically higher



What do the event generators say?



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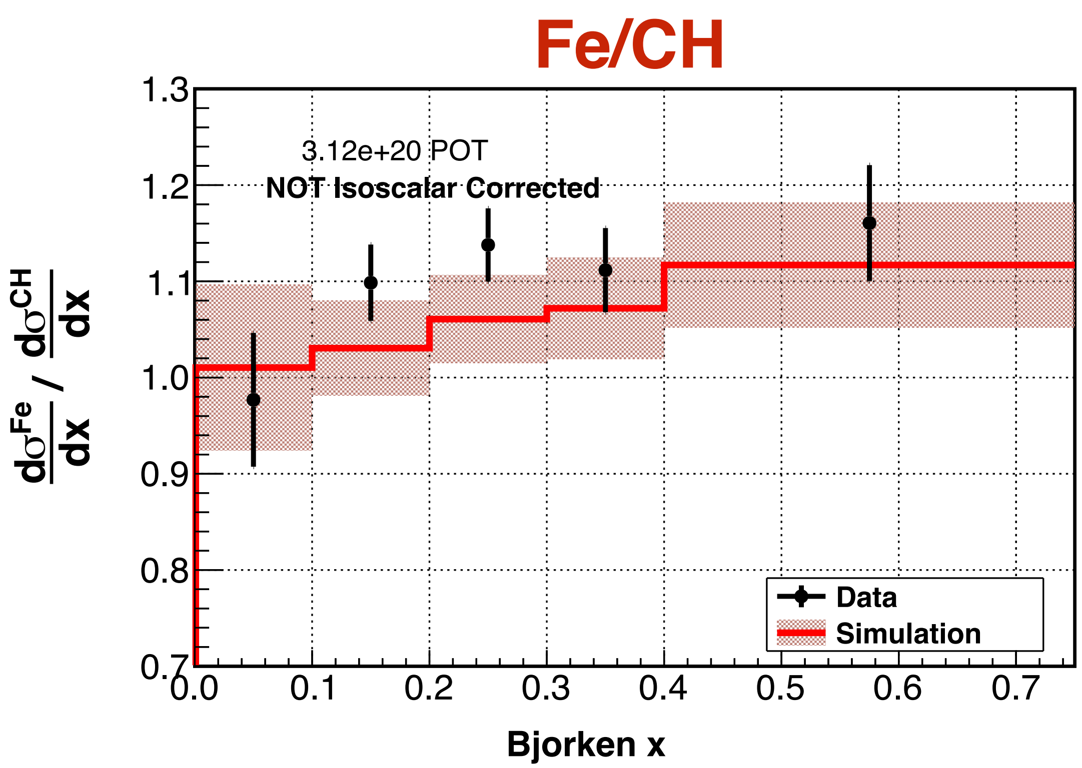
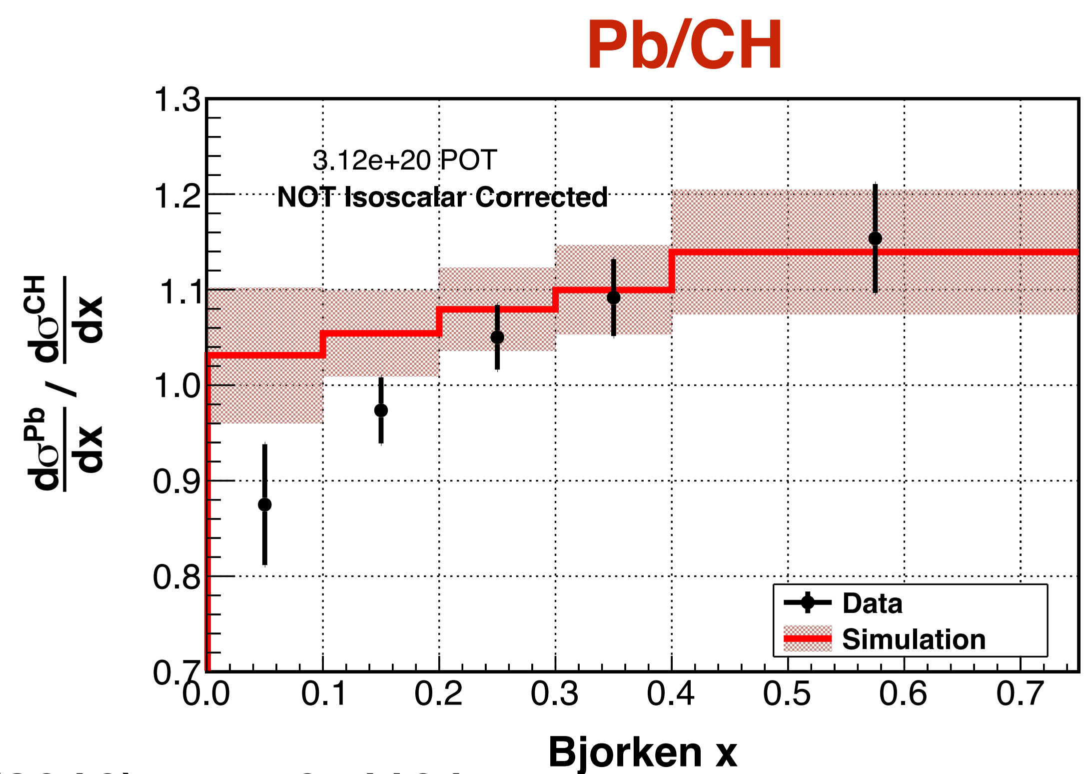
MINERvA DIS Cross Sections On Different Nuclei

- MINERvA measured deep inelastic ratios from nuclear targets to study x dependence nuclear effects, new analysis with more statistic is underway





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

Phys.Rev. D93 (2016) no.7, 071101

- The data suggest additional nuclear effects in the lowest x bin for Pb/CH
- In the region (0.3<x<0.75) we found good agreement between data and simulation
- New analysis in preparation with unprecedented statistics in Fe and Pb for neutrinos and antineutrinos

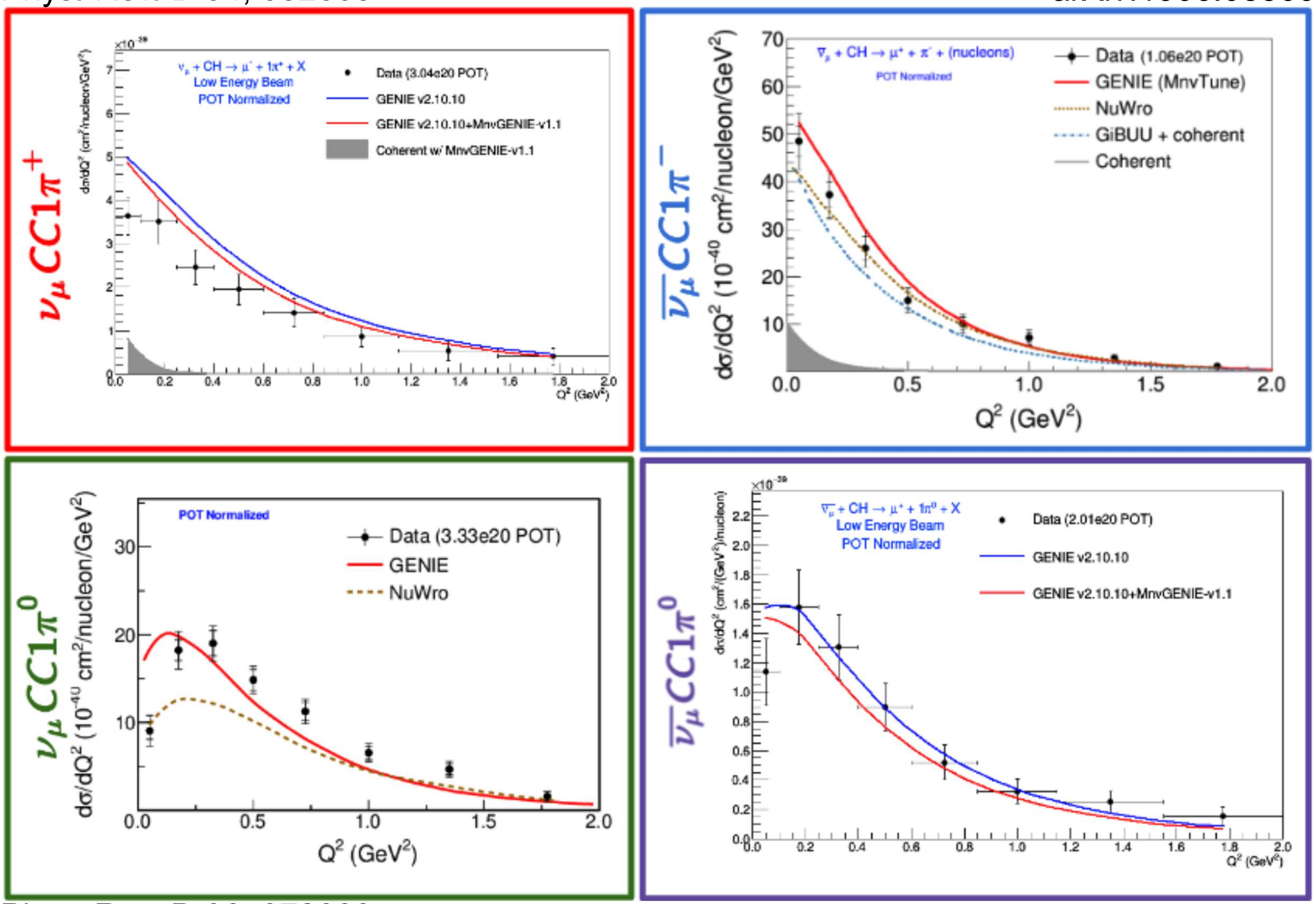
MINERvA Pion Production Measurements

- Several pion cross section measurements, MINERvA sees deficit of pion production at low Q^2

Phys. Rev. D 92, 092008

Phys. Rev. D 94, 052005

arXiv:1906.08300



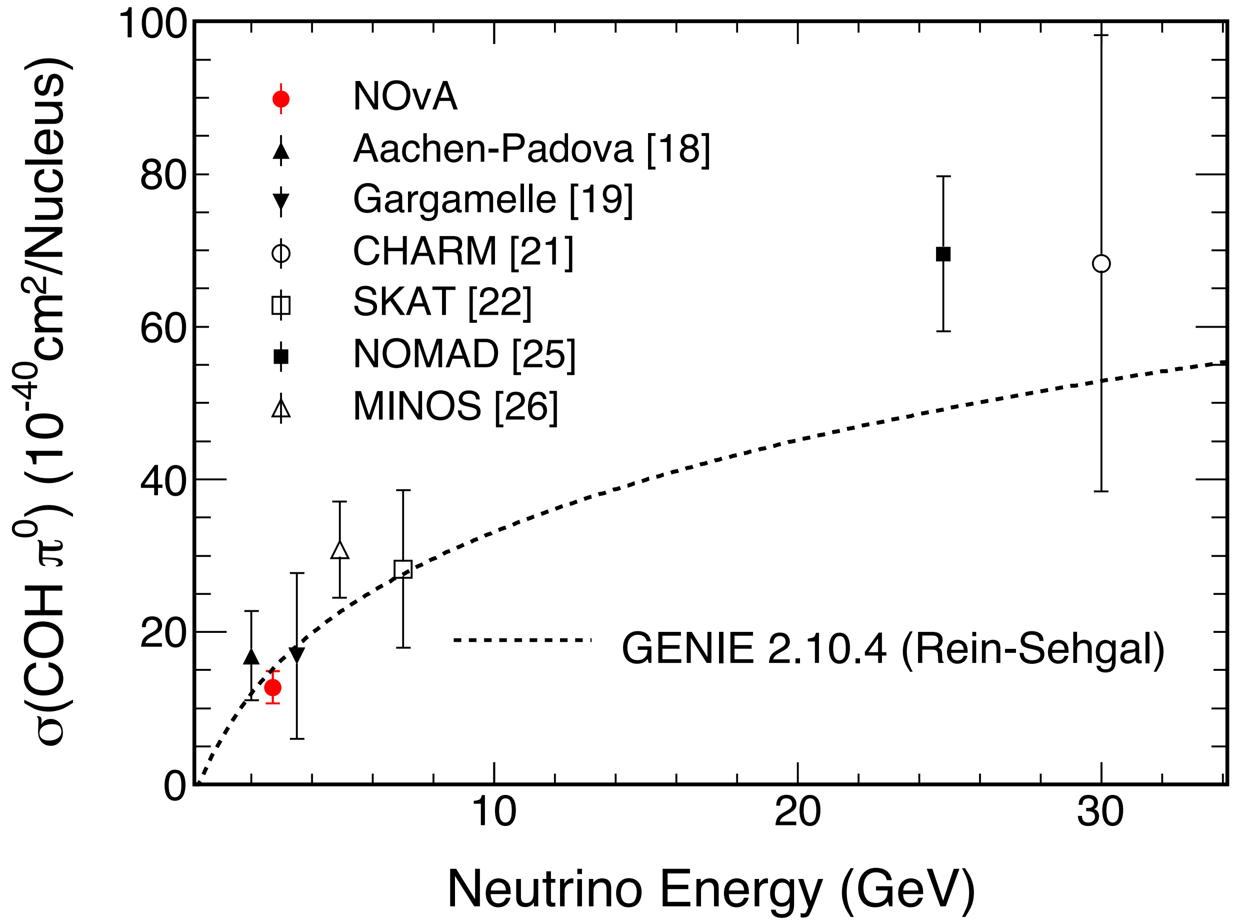
Phys. Rev. D 96, 072003

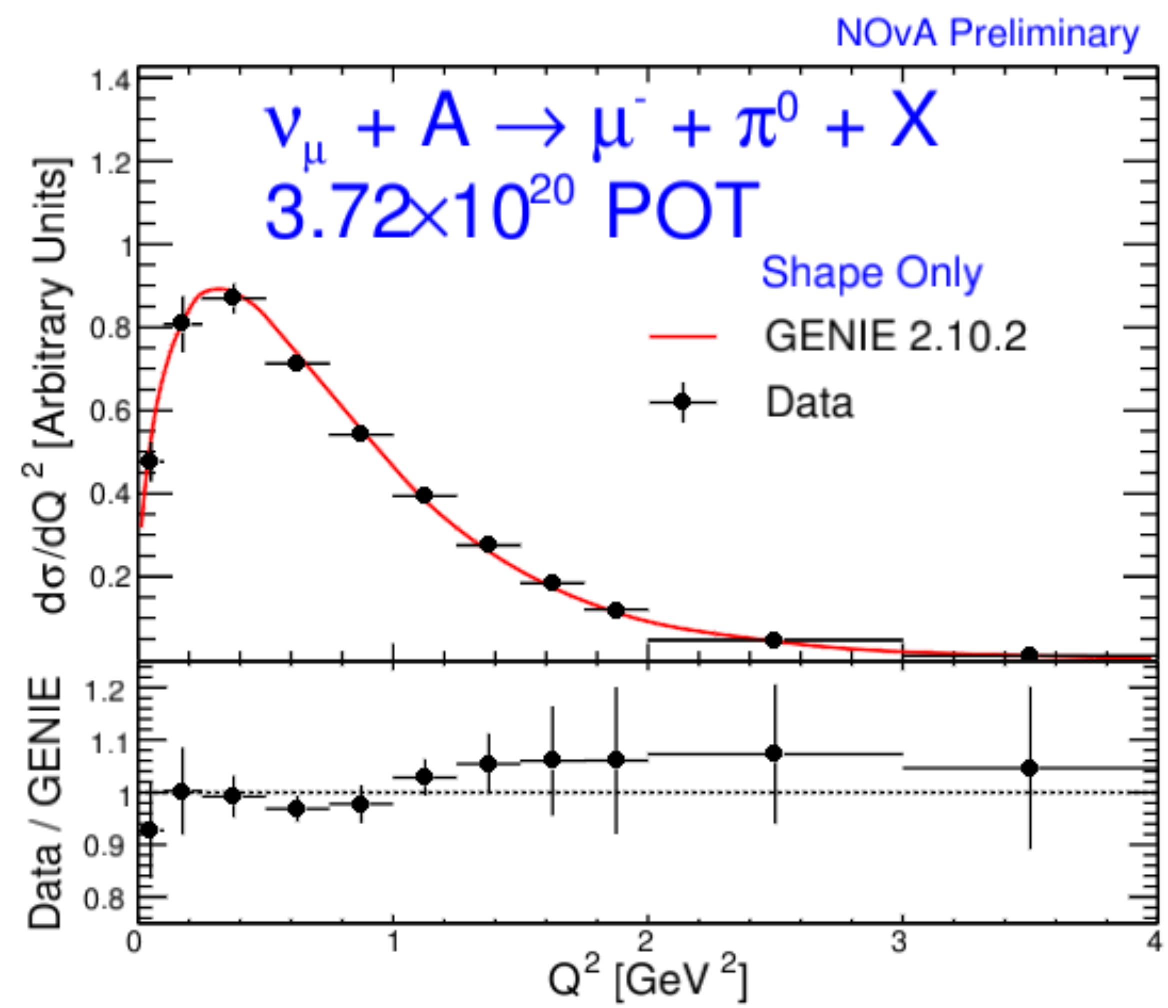
Phys.Lett. B749 (2015) 130-136

Phys. Rev. D 94, 052005

NOvA Neutral Current Coherent π⁰ and Charged Current semi-inclusive π⁰

- NOvA Near Detector measured neutral-current coherent π^0 production on a carbon-dominated target
- The flux-averaged cross section is consistent with the model prediction
- Generally consistent with GENIE predictions



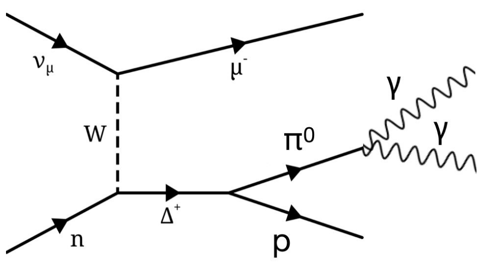


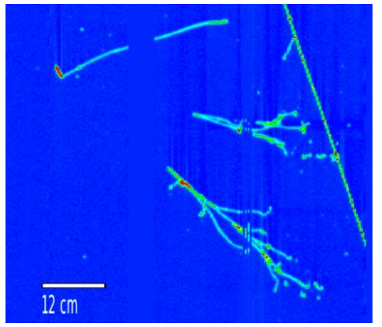
https://arxiv.org/abs/1902.00558

Fermilab Wine and Cheese Seminar, Dec 2017, Dan Pershey

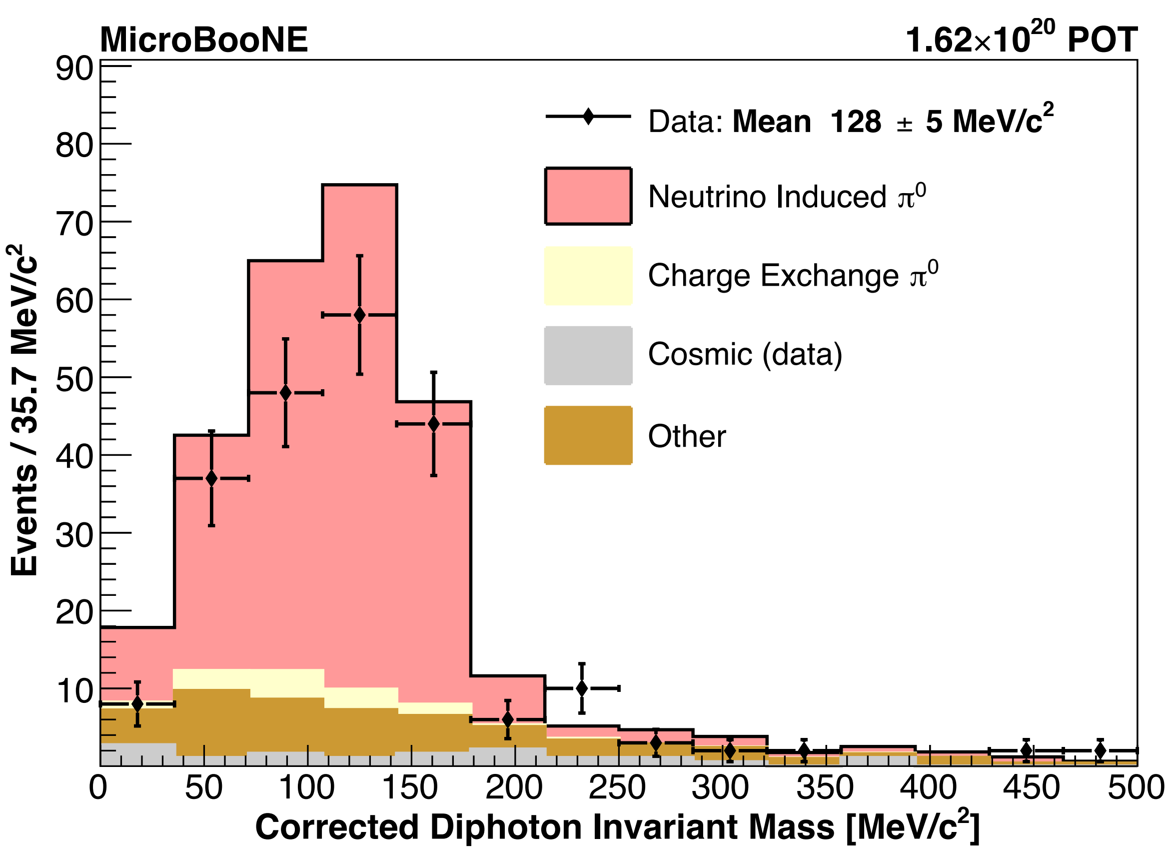
First Charged Current Π_0 Production on Argon

- First generation MicroBooNE analysis is a great demonstration of reconstruction in LArTPCs
- Invariant mass expected to be m=135 MeV

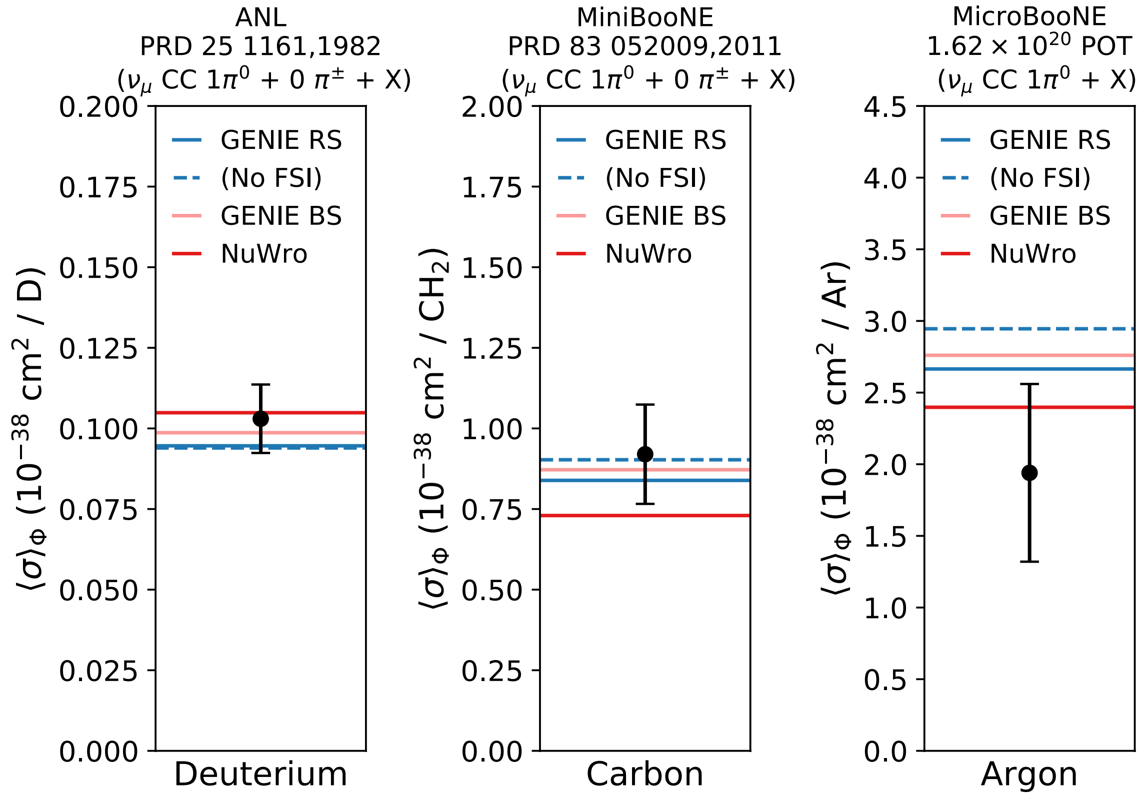




Reconstructed invariant mass of the two photon candidates associated to the neutrino interaction vertex



Results are compared to past measurements on lighter nuclei to compare the models predictions

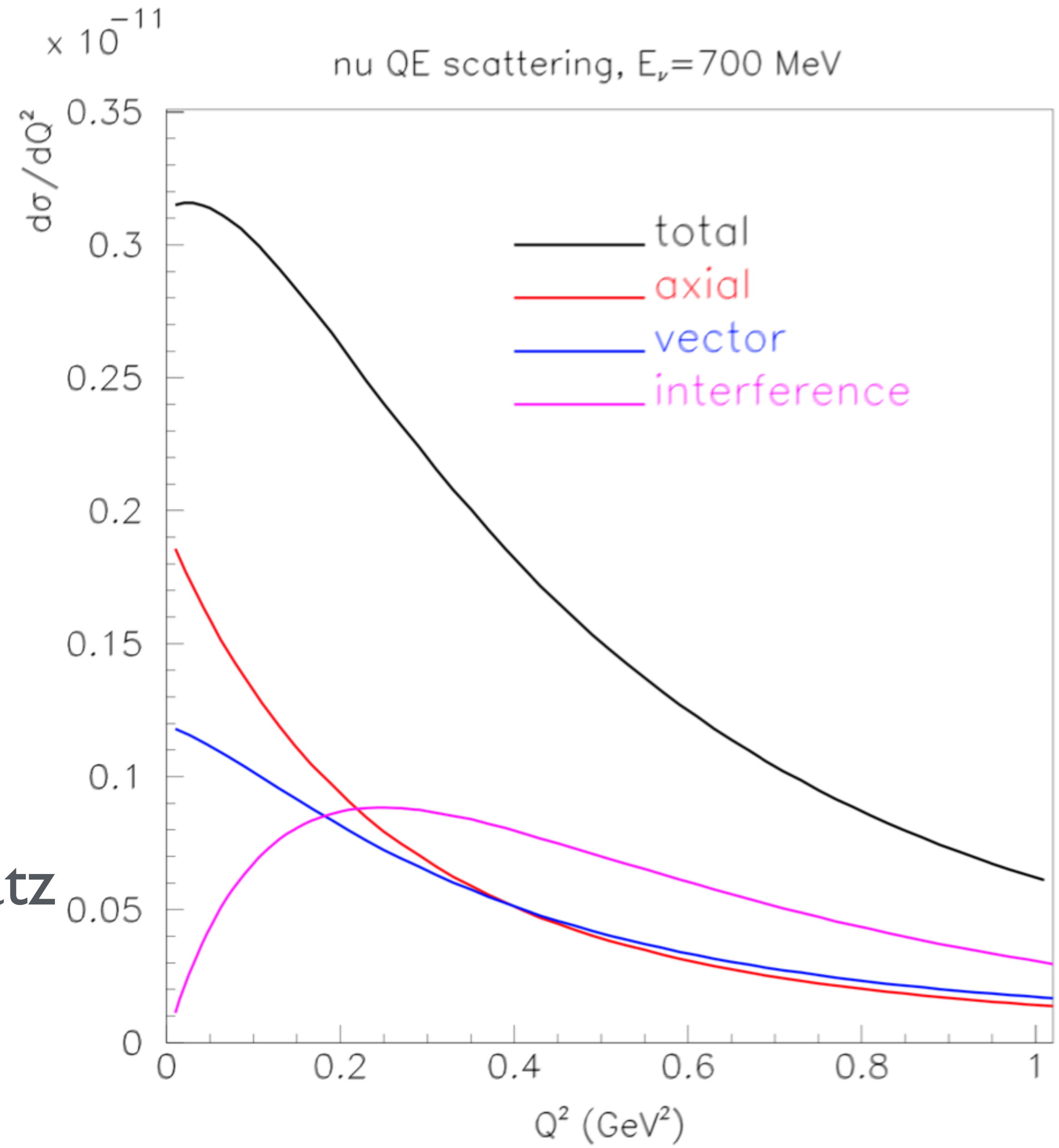


Phys.Rev. D99 (2019) no.9, 091102

Quasi-Elastic Scattering (CCQE)

- The Quasi-elastic process gives the largest contribution for the signal in many oscillation experiments
- We use a free nucleon CCQE formalism to determine the cross section

$$\frac{d\sigma}{dq^2} \propto (F_1, F_2, F_A)$$



- Depend on the form factors F_1, F_2 and the axial form factor FA
- The vector form factors F_1, F_2 are known from electron-nucleon scattering
- The axial form factor is described using an ansatz

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

- FA(0) is constrained from neutron beta decay and M_A is the axial mass

Axial Form Factor

- The dipole axial form factor ansatz:

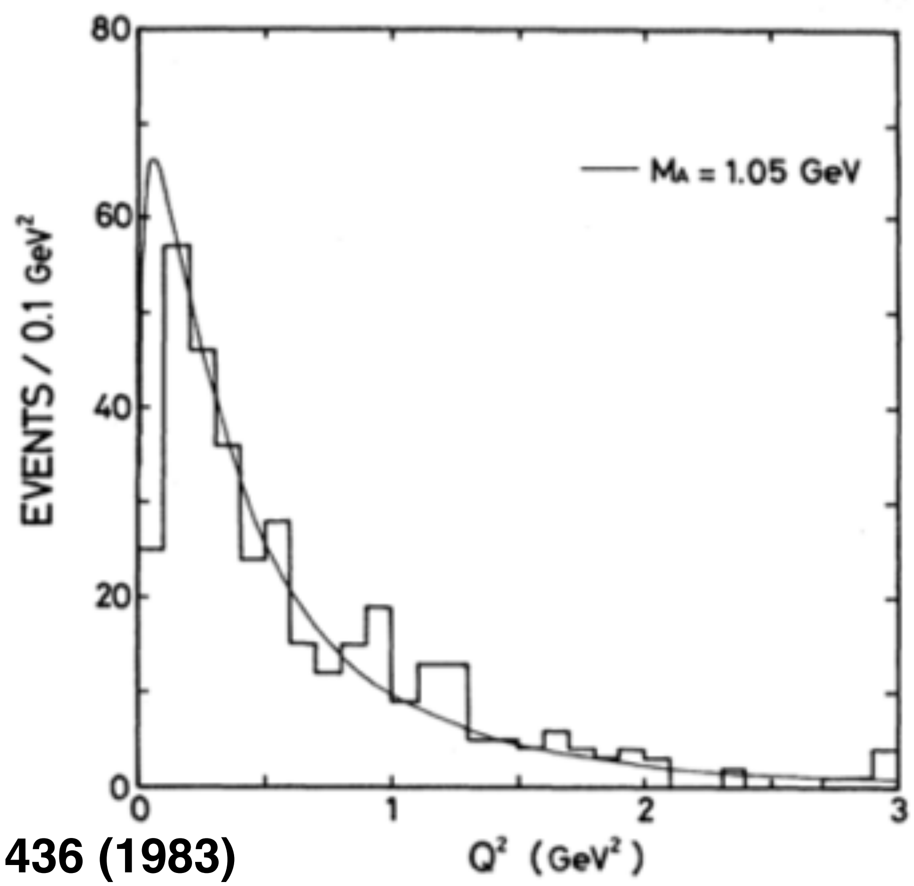
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

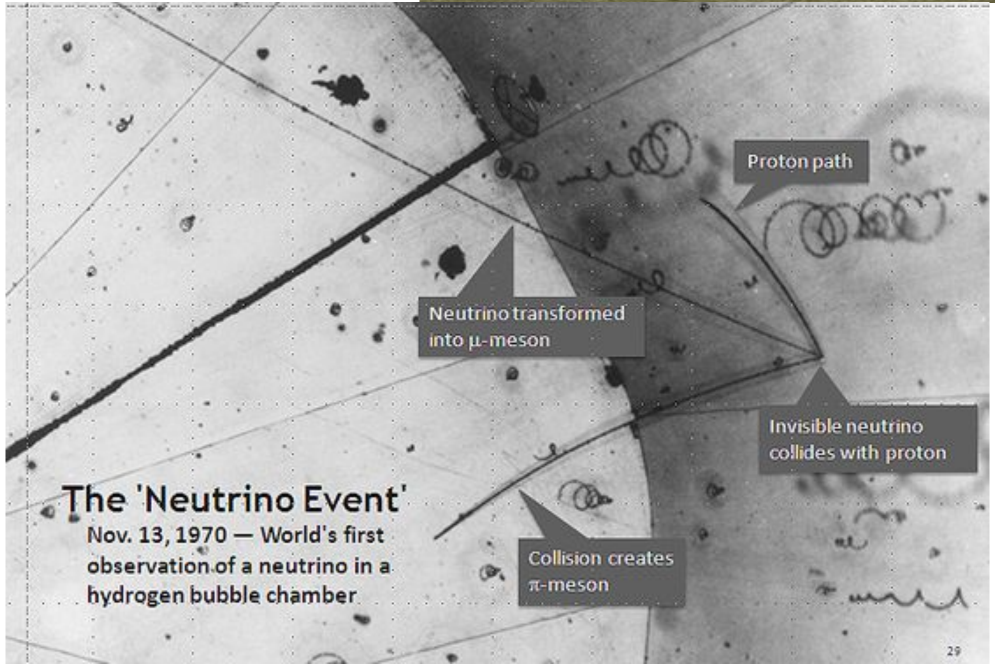
- Experiments with deuterium targets have employed this anzatz, obtaining a world average M_A

$$M_A = 1.014 \pm 0.014 GeV$$

Eur. Phys. J. C 53, 349 (2008)

Bubble chamber experiment at Fermilab





Kitagaki, PRD 28, 436 (1983)

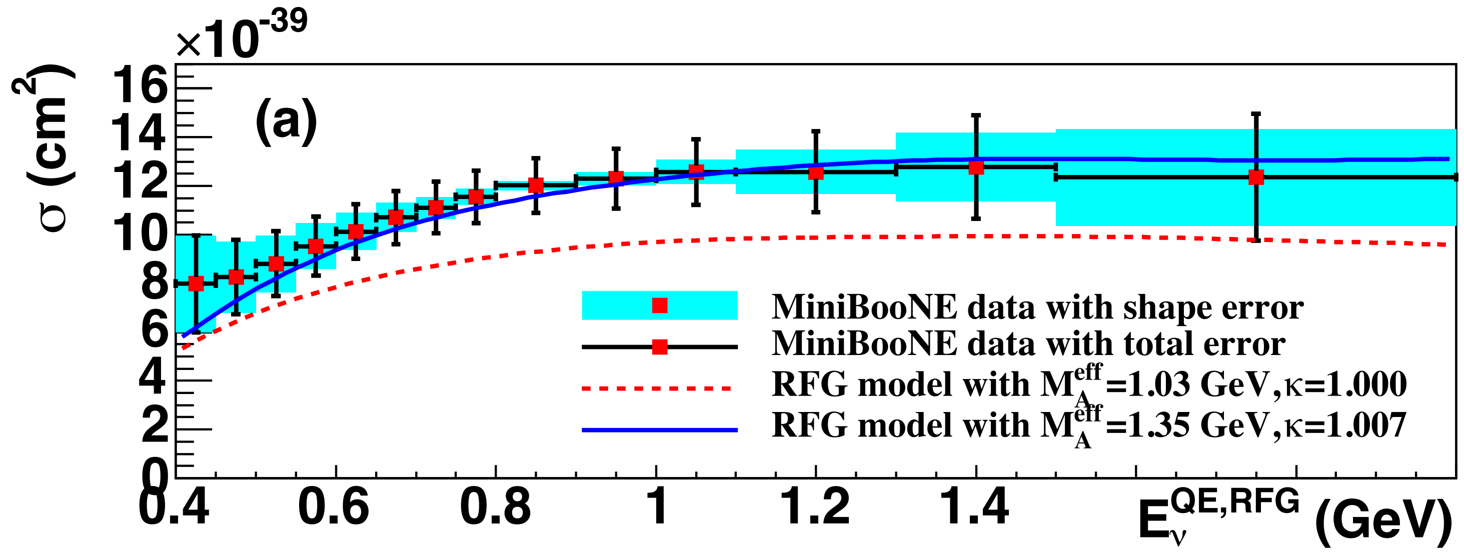
Axial Form Factor

- The dipole axial form factor ansatz:

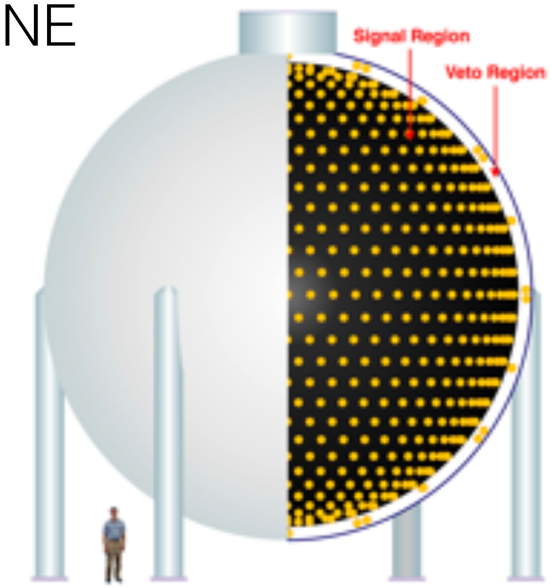
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

- Modern experiments using heavy targets, like carbon from MiniBooNE reported a higher axial mass

$$M_A = 1.35 \pm 0.17 GeV$$



MiniBooNE



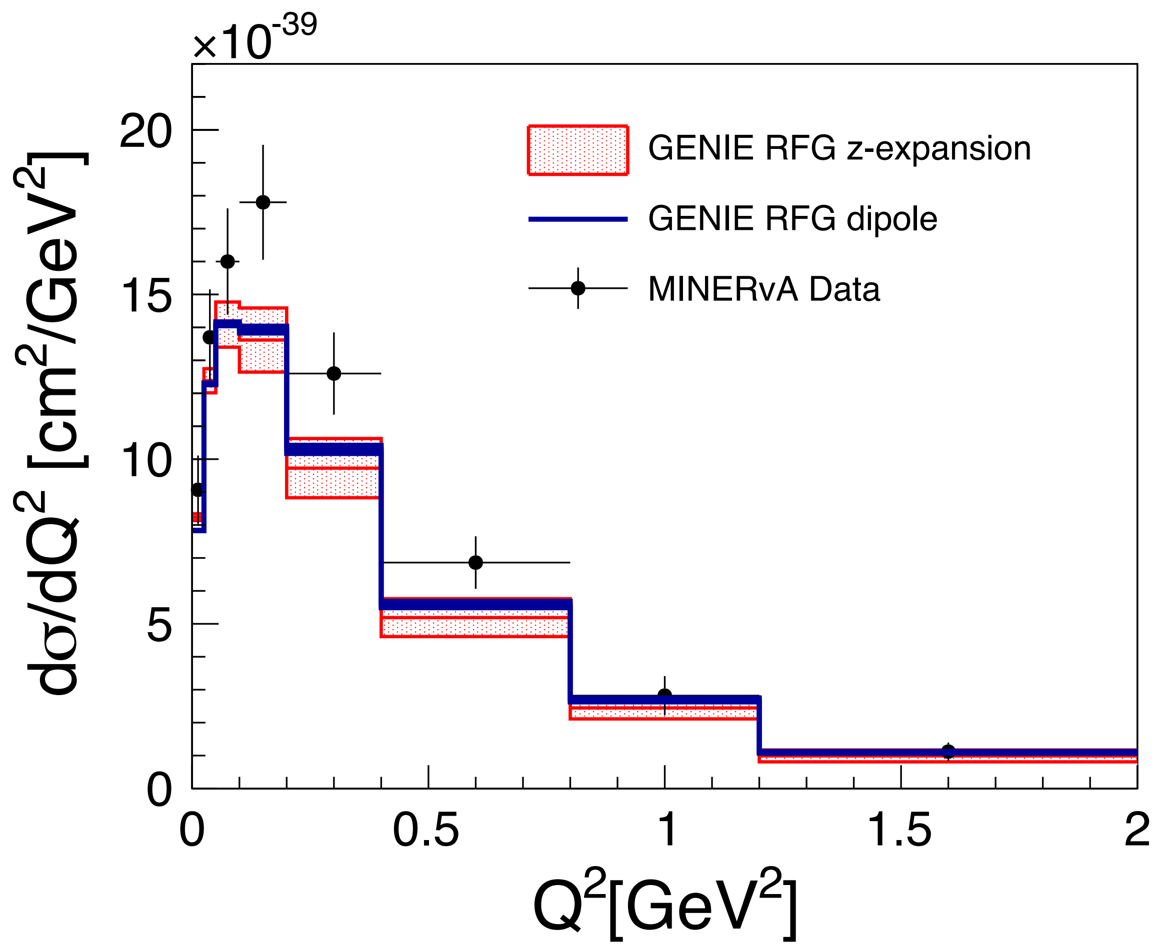
- Other experiments such as K2K, SciBar and MINOS find similar higher axial mass compared with the world average
- **This high mA is an effective parameter that we expect represents multi-nucleons effects, and not directly the form factor itself**

Axial Form Factor

- A model independent description of the axial form factor called z-expansion is derived in Phys. Rev. D84 (2011)
- The form factor can be expressed as a power series of a new variable z

$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$

- where the expansion coefficients a_k are dimensionless numbers representing nucleon structure information
- Derived from first principles of QCD
- Extensively used in meson decay

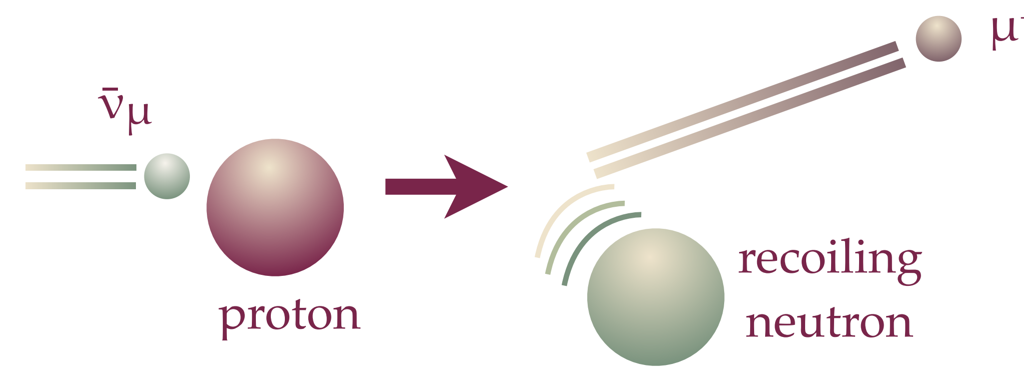


Aaron Meyer, MB, Richard Gran and Richard Hill, Phys. Rev D93(2016)

Double Differential Cross Sections (Antineutrinos and Neutrinos)

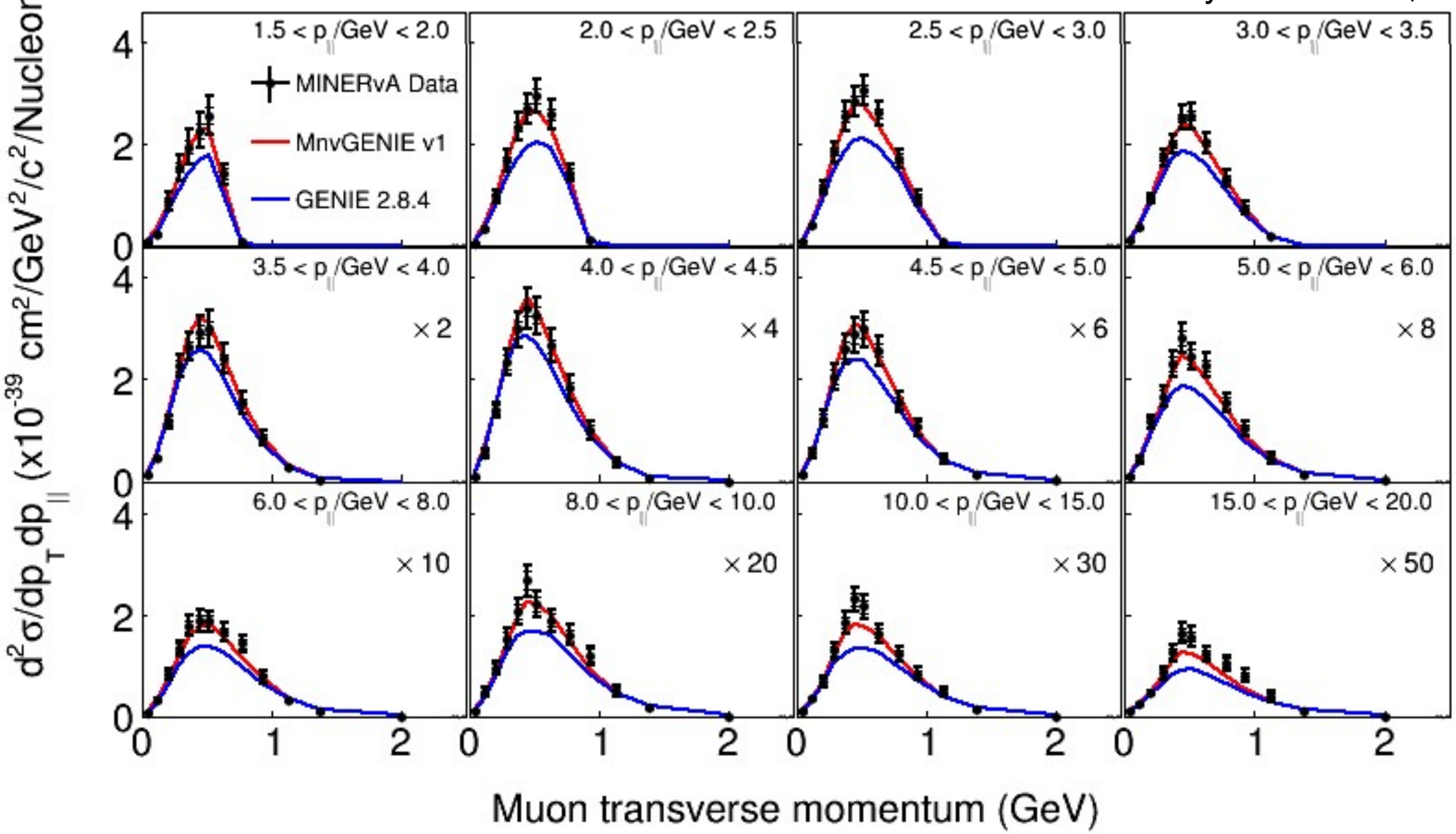
- Using the kinematics of the muon
- Data agrees with the simulation that includes nuclear effects (RPA and 2p2h)

$$\frac{d^2\sigma}{dP_{T_\mu}dP_{Z_\mu}}$$



Phys. Rev. D 99, 012004

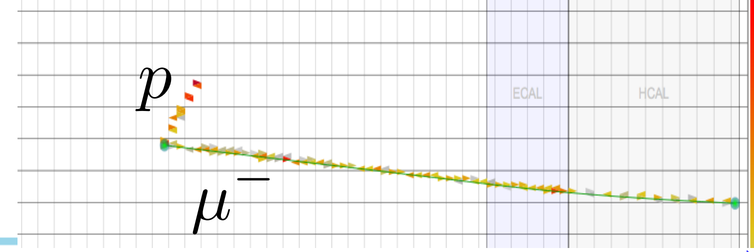
MINERvA



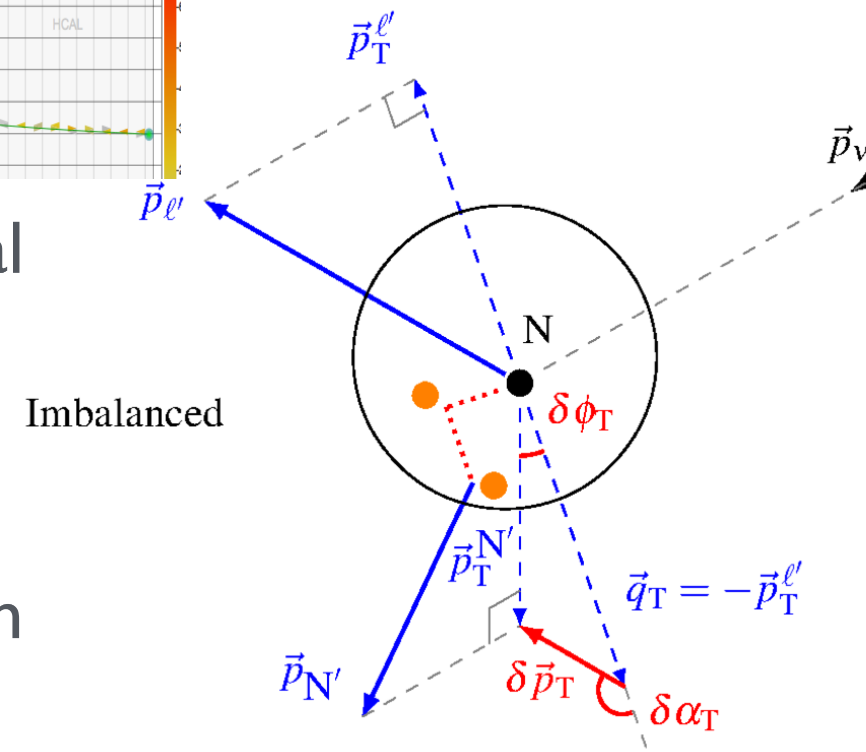
Antineutrinos: Phys.Rev. D97 (2018) no.5, 052002

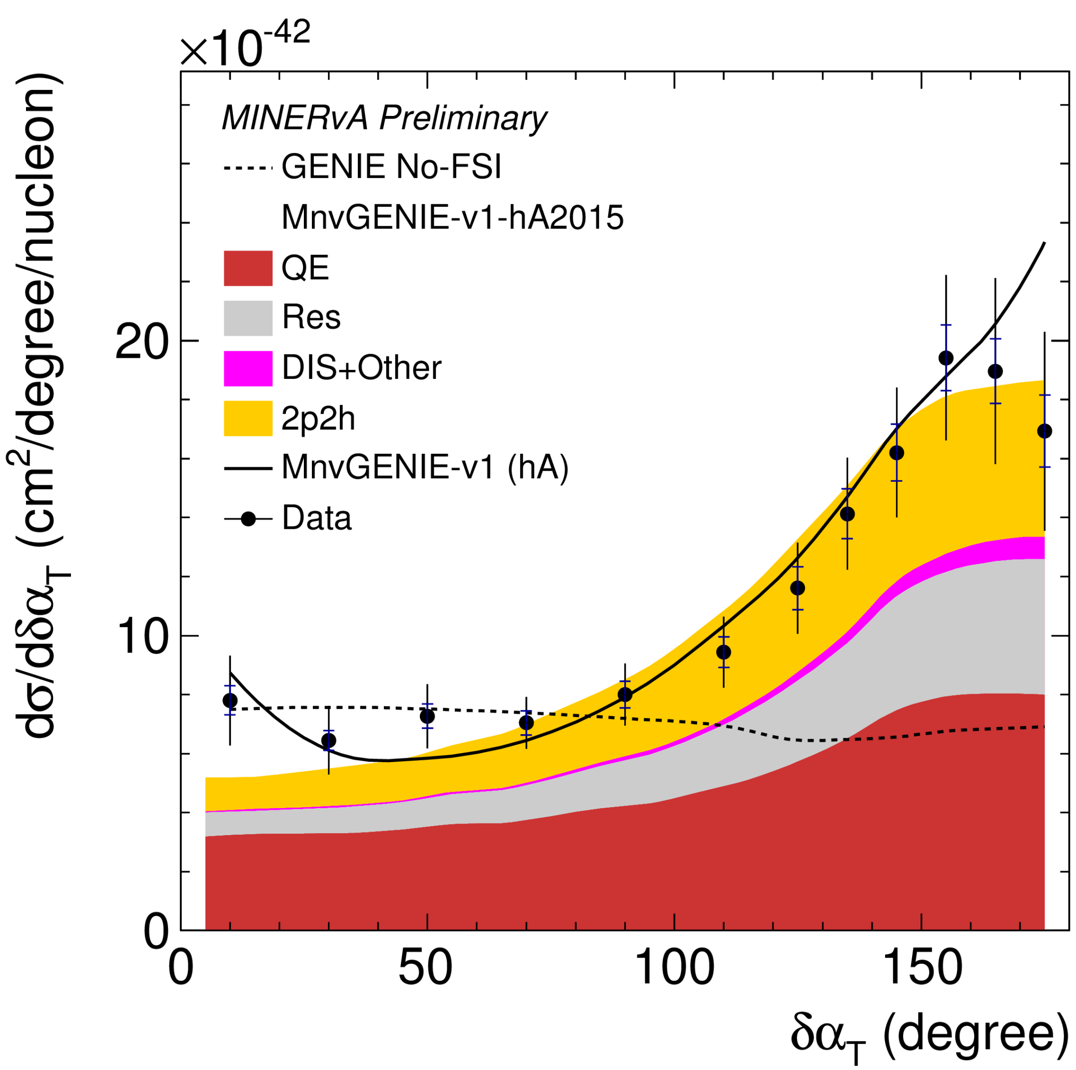
Fermilab

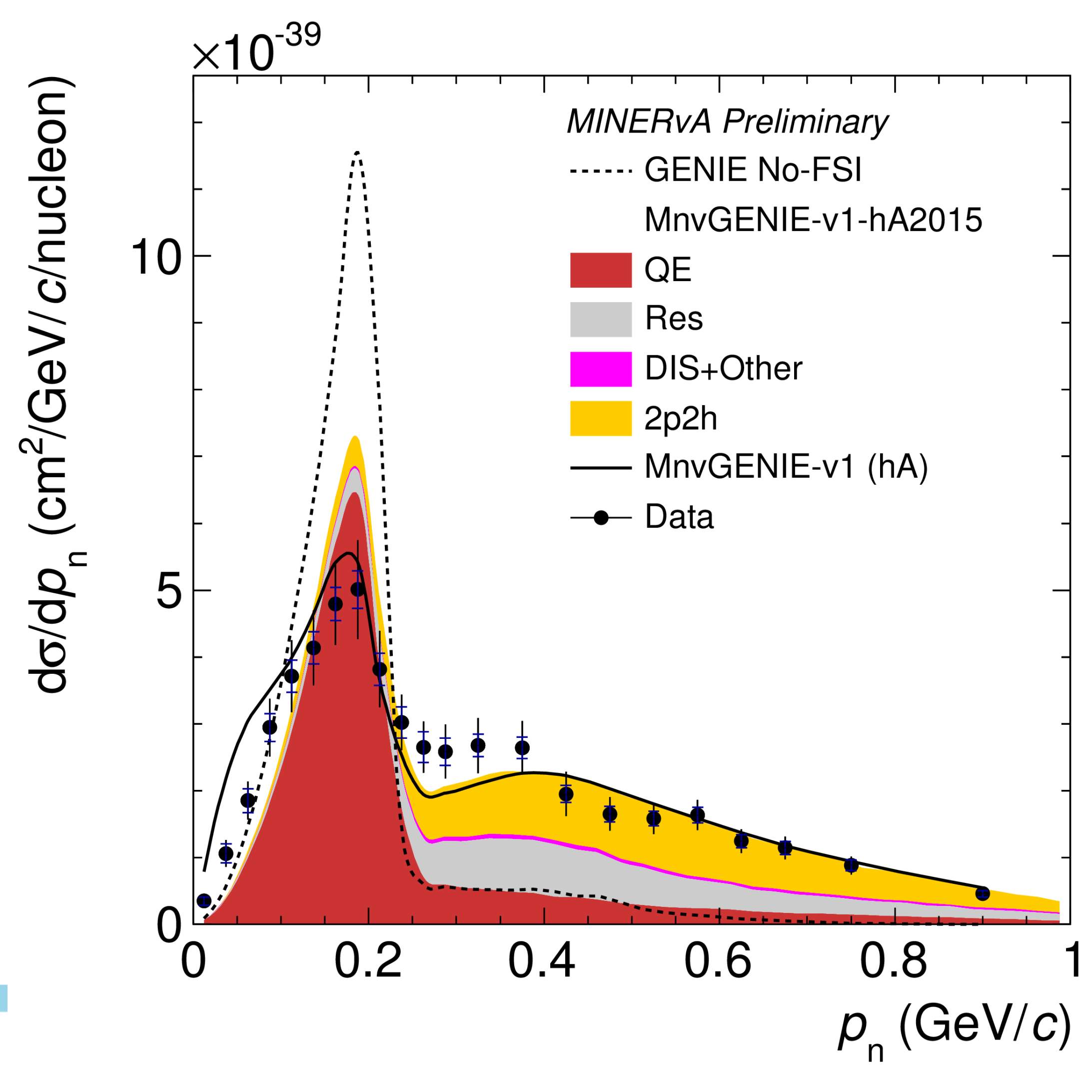
MINERvA New Observables



- Probing final state nuclear effects using the transverse imbal of the leading proton and the lepton
- First differential cross section in initial struck neutron momentum
  - Useful to constrain initial nuclear effects, deficiencies in th at low and mid region of the neutron momentum







Phys.Rev.Lett. 121 (2018) no.2, 022504

Joint Group Between Theorists and Experimentalists at Fermilab

What we have

- Rich neutrino program at Fermilab
- Remaining questions of neutrino oscillation
- Neutrino phenomenology
- HEP theory
- Experimentalists
- Software expertise (collider, lattice, ν)

What we need

- Communication between theorists and experimentalists
- Accurate models
- New models to be developed and incorporated in the simulations
- Detailed understanding of each of the component of theory

- Walter Giele, Adi Ashkenazi and Minerba Betancourt are leading the effort
- Members of the group are Fermilab scientists, distinguish Fellows, intensity Frontiers and neutrino physics center fellows

Joint group between theorists and Experimentalists

- We have been meeting once a month since 2017
  - Details at Indico https://indico.fnal.gov/category/724/
- We identified specific topics for the working groups and started to work
- Interfacing theory and GENIE:
  - Nuclear ab initio
  - DIS
  - Radiative corrections and nue/numu cross section differences
  - Lattice QCD
- Phenomenology

- We welcome new collaborators!

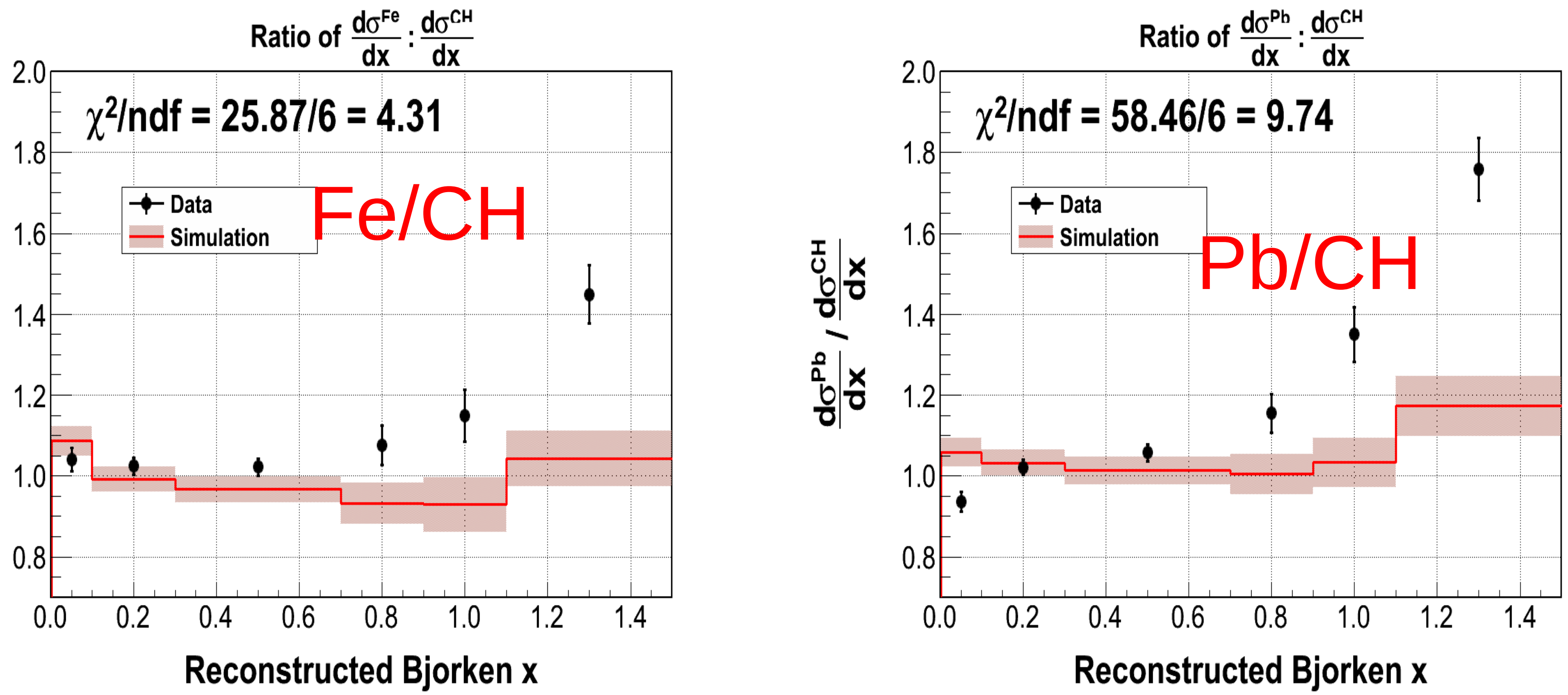
Summary

- Several challenges from the theoretical model side and experimental side to understanding neutrino interactions
- Many theoretical developments to model meson exchange current and nuclear long range correlations
- More development needed for pion production and deep inelastic scattering
- Rich set of new cross section measurements from MINERvA, MicroBooNE and NOvA
  - Data -model disagreement across many experiments
- We are learning a lot from neutrino-nucleus interactions and building a rich set of cross section results for the oscillation experiments
- Oscillation experiments depend on modeling nuclear effects correctly and knowledge of cross sections to a few percent for precision oscillation measurements

BackUp Slides

MINERvA Inclusive Cross Sections On Different Nuclei

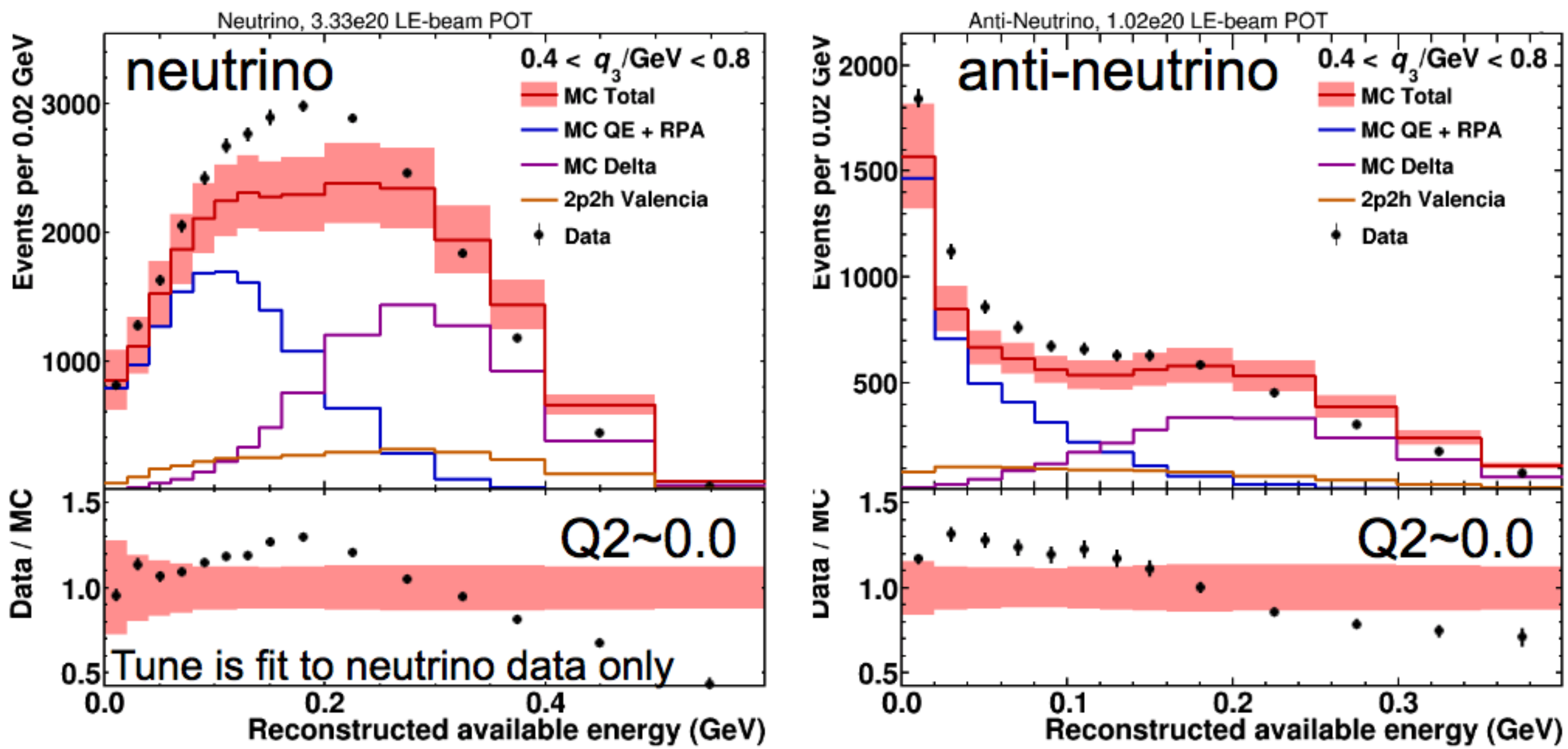
- MINERvA measured inclusive charged current cross section ratios as a function of Bjorken x $x = \frac{Q^2}{2ME_{had}}$
- x corresponds to the fraction of the initial nucleon's momentum that is carried by the struck quark
- Model of nuclear effects is wrong for heavier nuclei
- The high X region greater than one is dominated by short range correlation



Phys.Rev.Lett. 112 (2014) no.23, 231801

The MINERvA Tune

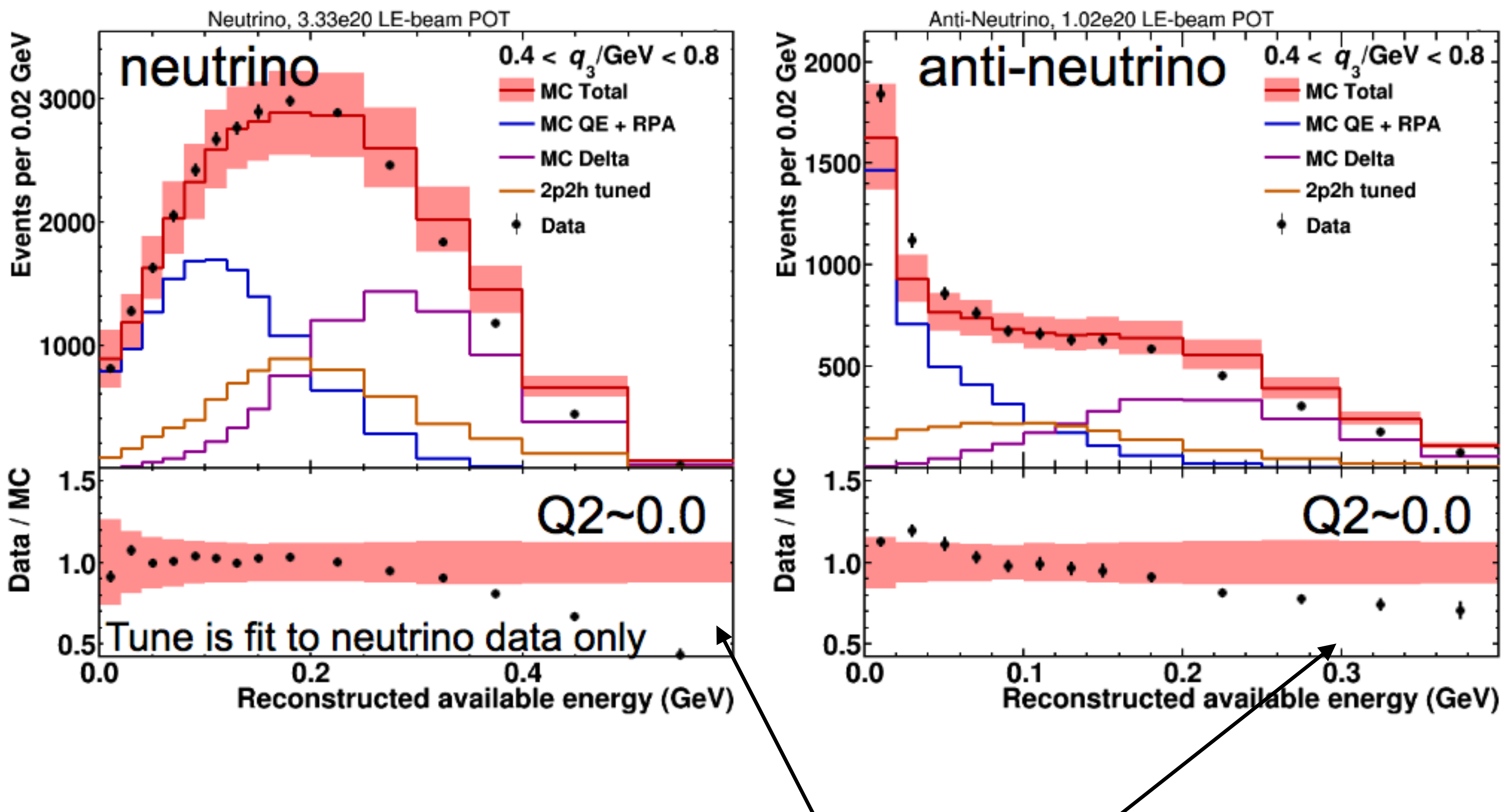
- Adding in models of multi nucleon and RPA improves agreement in some regions



- Performed an empirical fit to scale up the multi nucleon contribution
- The fit is performed using neutrino data, then applied in antineutrino analysis

The MINERvA Tune

- The tune from neutrino data also agrees with antineutrino data



- Remaining problem is the region with pion production