Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Lecture 2

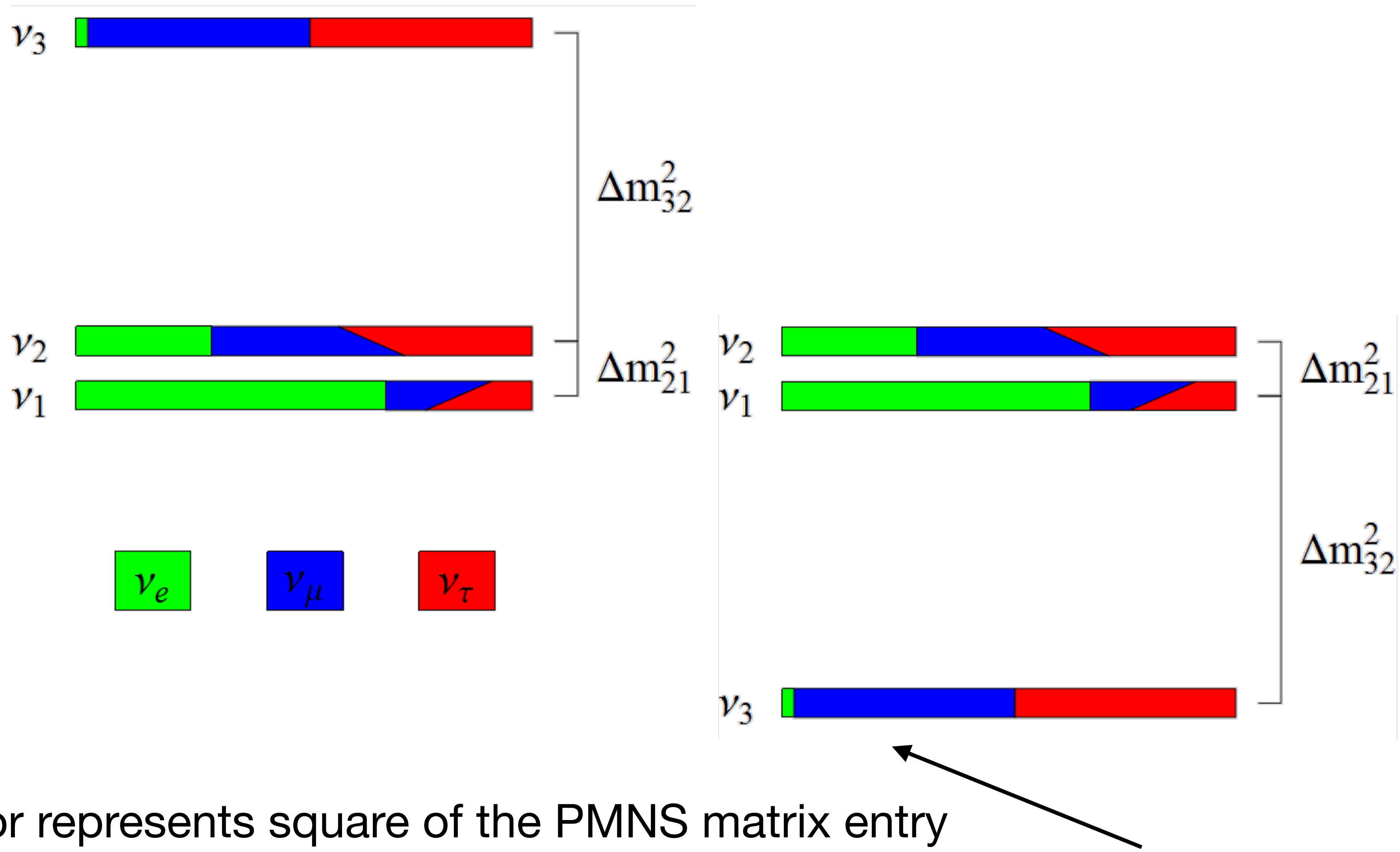
Minerba Betancourt, Fermilab

23 July 2019

Outline

- Follow up from yesterday
- How we produce a neutrino beam
- Neutrino interactions
- Examples of nuclear effects in neutrino interactions
- Cross section measurements

Follow up from Yesterday



Each color represents square of the PMNS matrix entry
For example, the tiny green band (electron) in the v3 line
|U_e3|^2 = sin^2(theta_13) = 0.02

Addressing the Remaining Questions

- Oscillation probability for 3 flavor with matter effect included

$$P(\nu_\mu(\bar{\nu_\mu}) \to \nu_e(\bar{\nu_e})) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$\mp 2\alpha \sin\theta_{13} \sin\delta_{cp} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$
$$+ 2\alpha \sin\theta_{13} \cos\delta_{cp} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

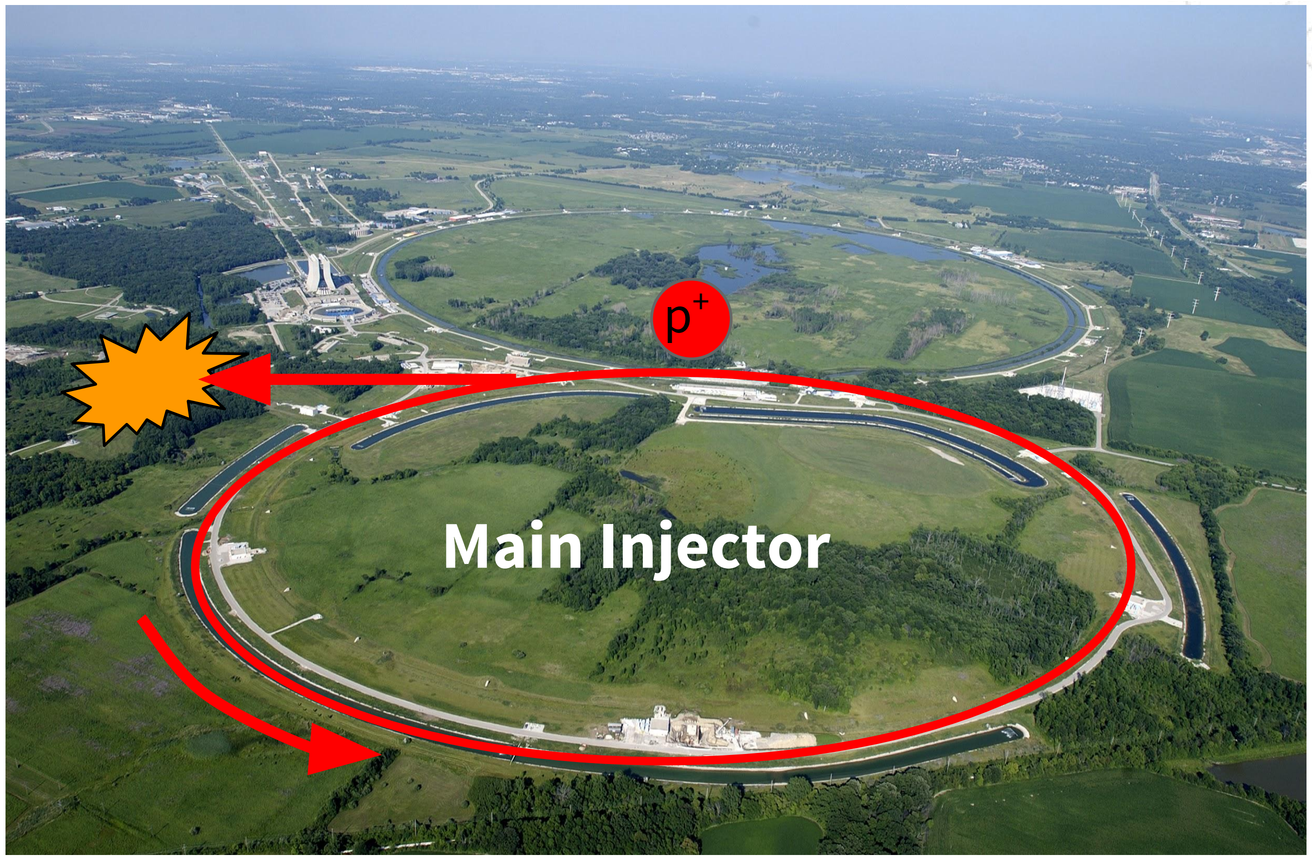
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \frac{\pi}{2hc} * \frac{\Delta m^2_{31} * L}{E} = 1.27 * \frac{\Delta m^2_{13}/[eV^2] * L/[km]}{E/[GeV]}$$

$$A = \pm G_f N_e L/\sqrt{2}\Delta = \pm 7.56 \times 10^{-5} * \frac{\rho/[g/cm^{-3}] * E/[GeV]}{\Delta m^2_{13}/[eV^2]}$$

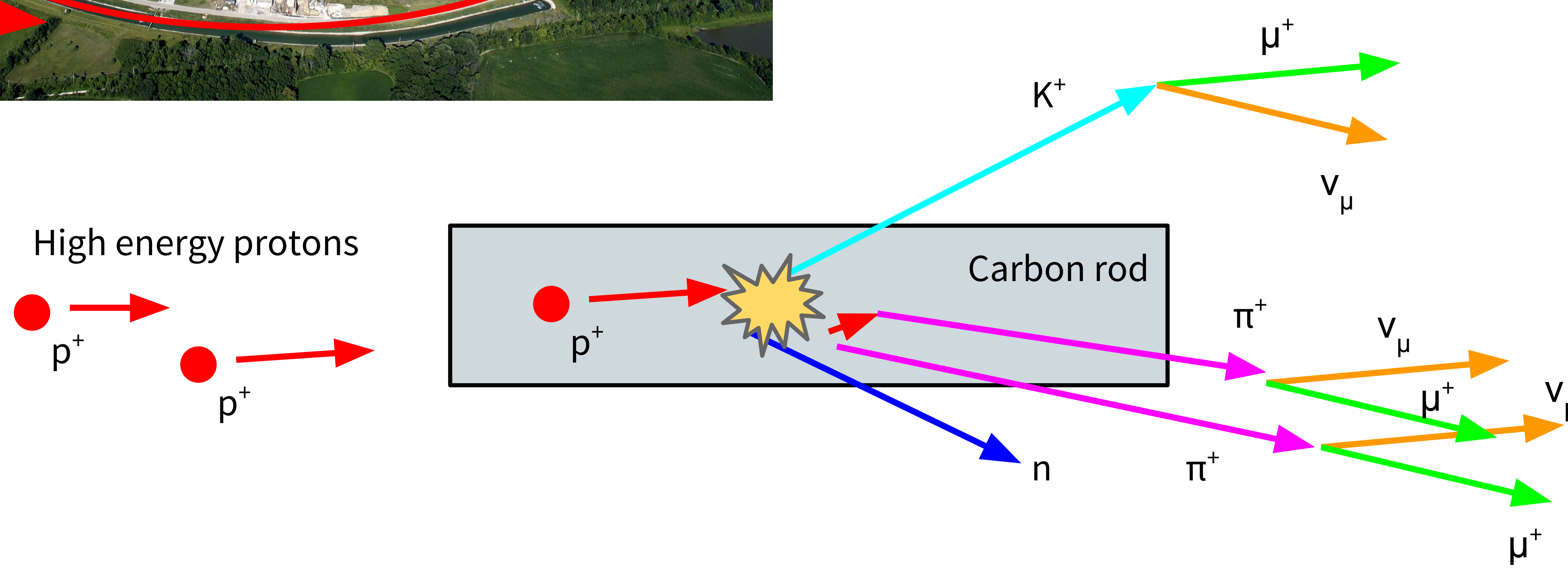
- In which ρ is the density of crust, $\sim 3\ \mathrm{g/cm^{-3}}$
- Δm^2_{13} Is the mass splitting between ν_1 and ν_3, $m^2_{\nu_3} - m^2_{\nu_1}$ which is positive for normal hierarchy and negative for inverted mass hierarchy
- The sign in front A is positive when it is in the neutrino mode and negative for antineutrino mode

Fermilab

How to make a neutrino beam



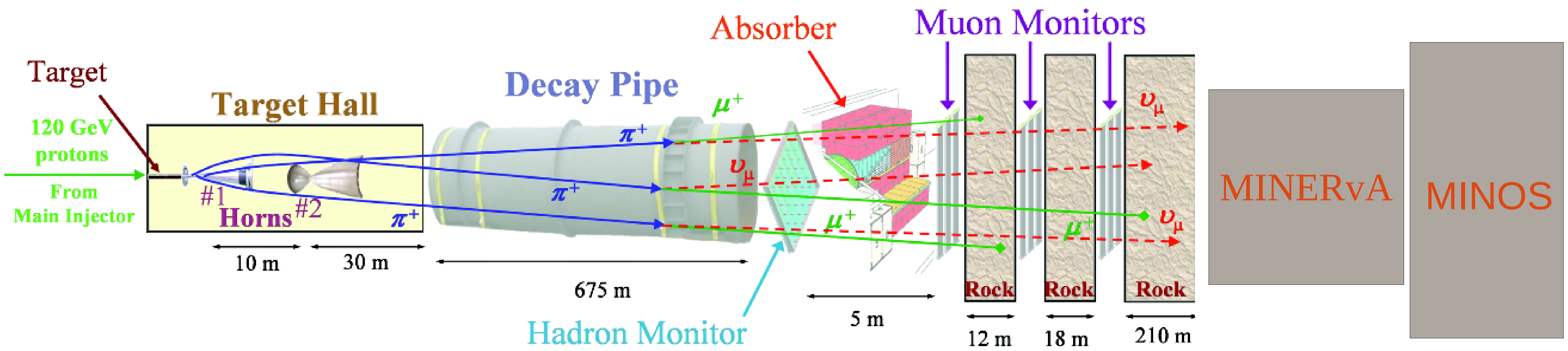
- Protons hit carbon
- Charged pions are produced
- Pions decay to neutrinos



Fermilab

Neutrinos From Accelerators

- A beam of protons interact with a target and produce pions and kaons

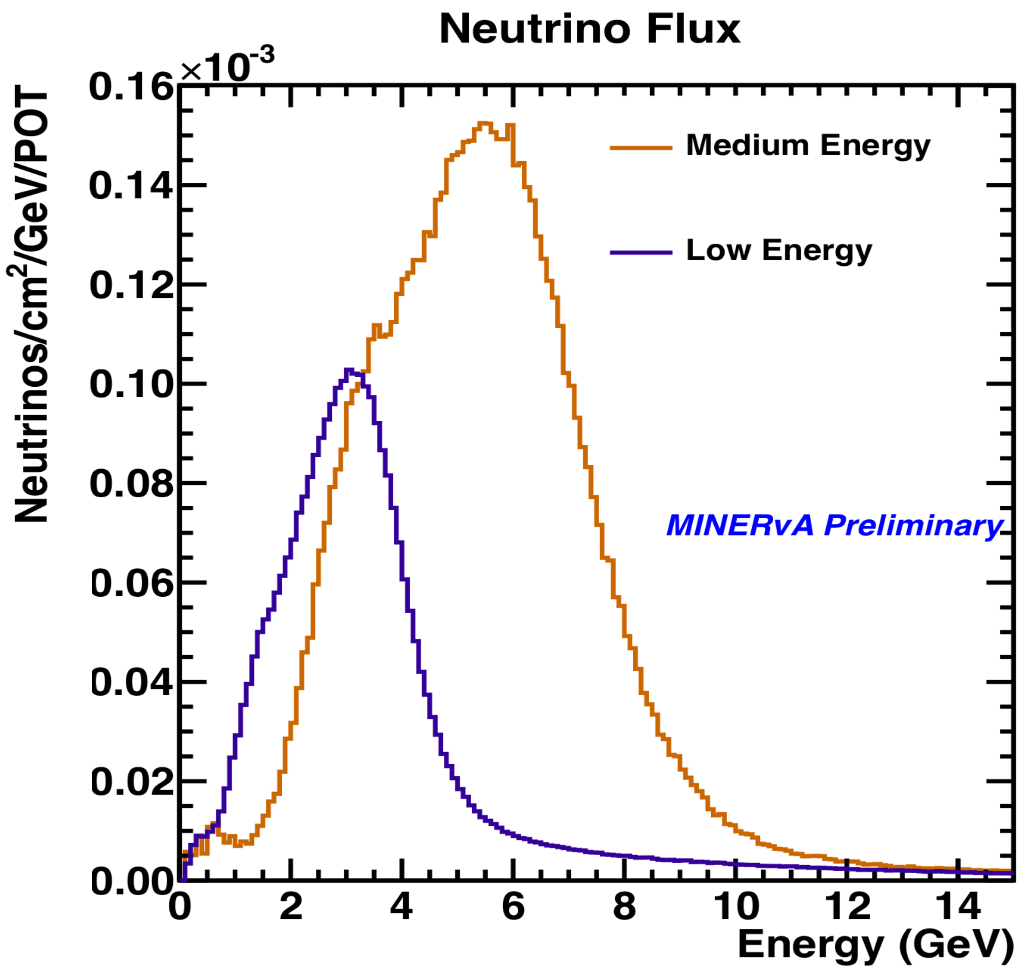


- Focusing system (2 horns, with current, emitting B field)
- Decay region (large pipe, filled with helium)
- Monitors and absorbers
- Neutrino beam produces mainly ν_μ and a small component of ν_e

Fermilab

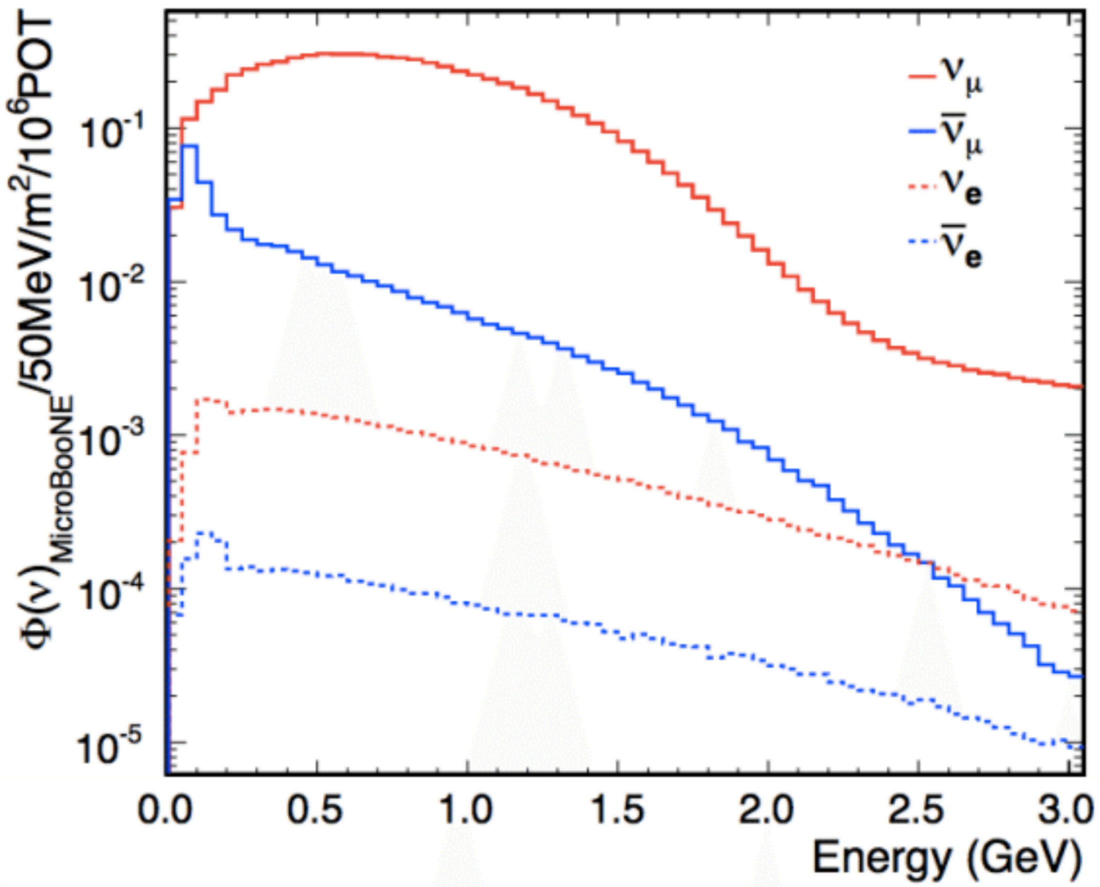
Neutrino Energy Spectrum from NuMI

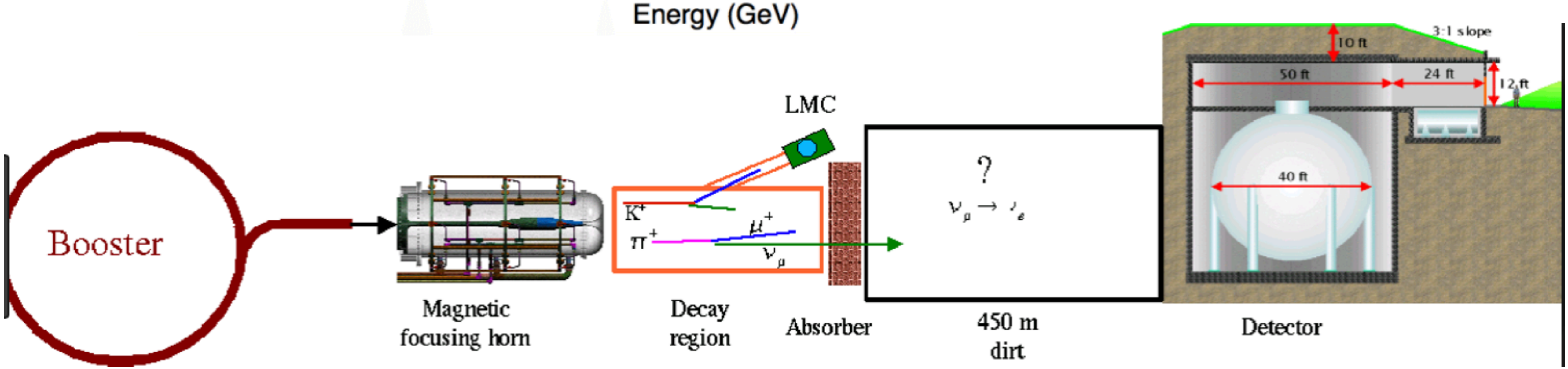
- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra
- This allows a study of neutrino interaction physics across a broad neutrino energy range
- Neutrino oscillation experiments use interactions in the near and far detectors to study oscillation physics



Fermilab

Neutrinos from the Booster





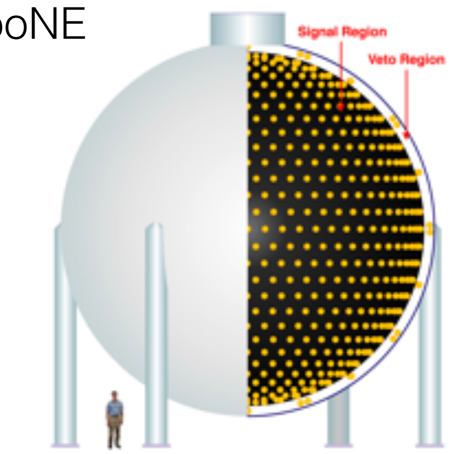
8 GeV protons

Fermilab

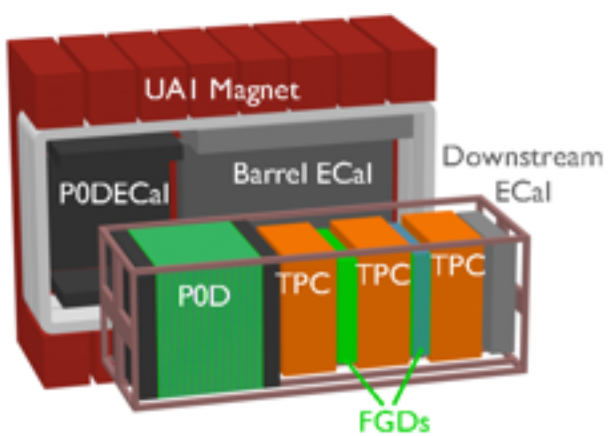
Cross Section Experiments

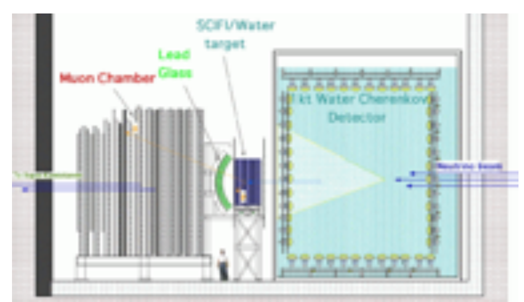
- Modern neutrino experiments using neutrino from accelerators
  - Different detector technologies and targets:
    - Oxygen, carbon, iron, liquid argon, helium, lead..
  - Different neutrino beams
- Common goal for all the experiments:
  - Study neutrino interactions

MiniBooNE



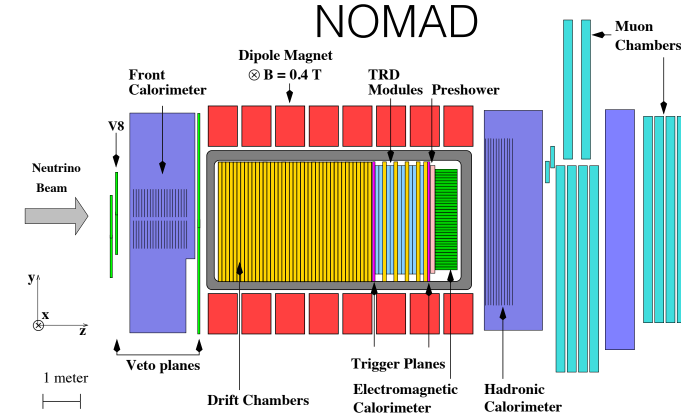
T2K





K2K

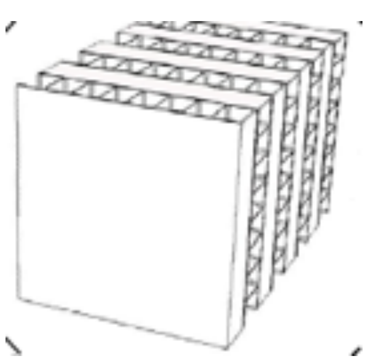
NOMAD



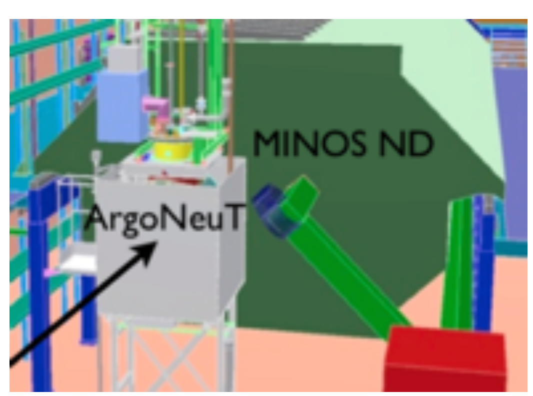
Argonut

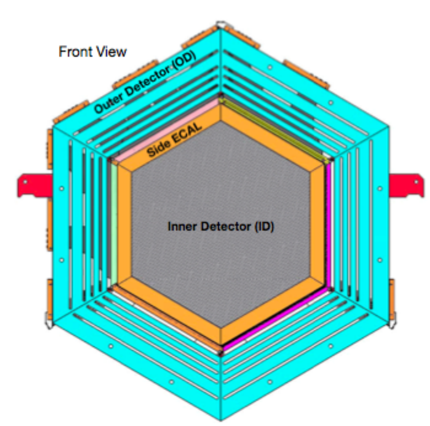
Minerva

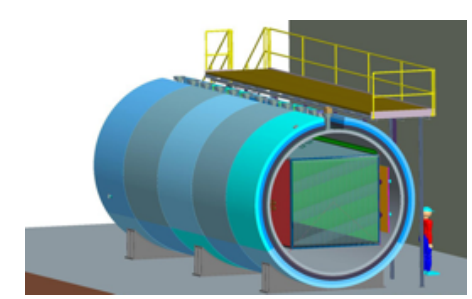
MicroBooNE



NOvA

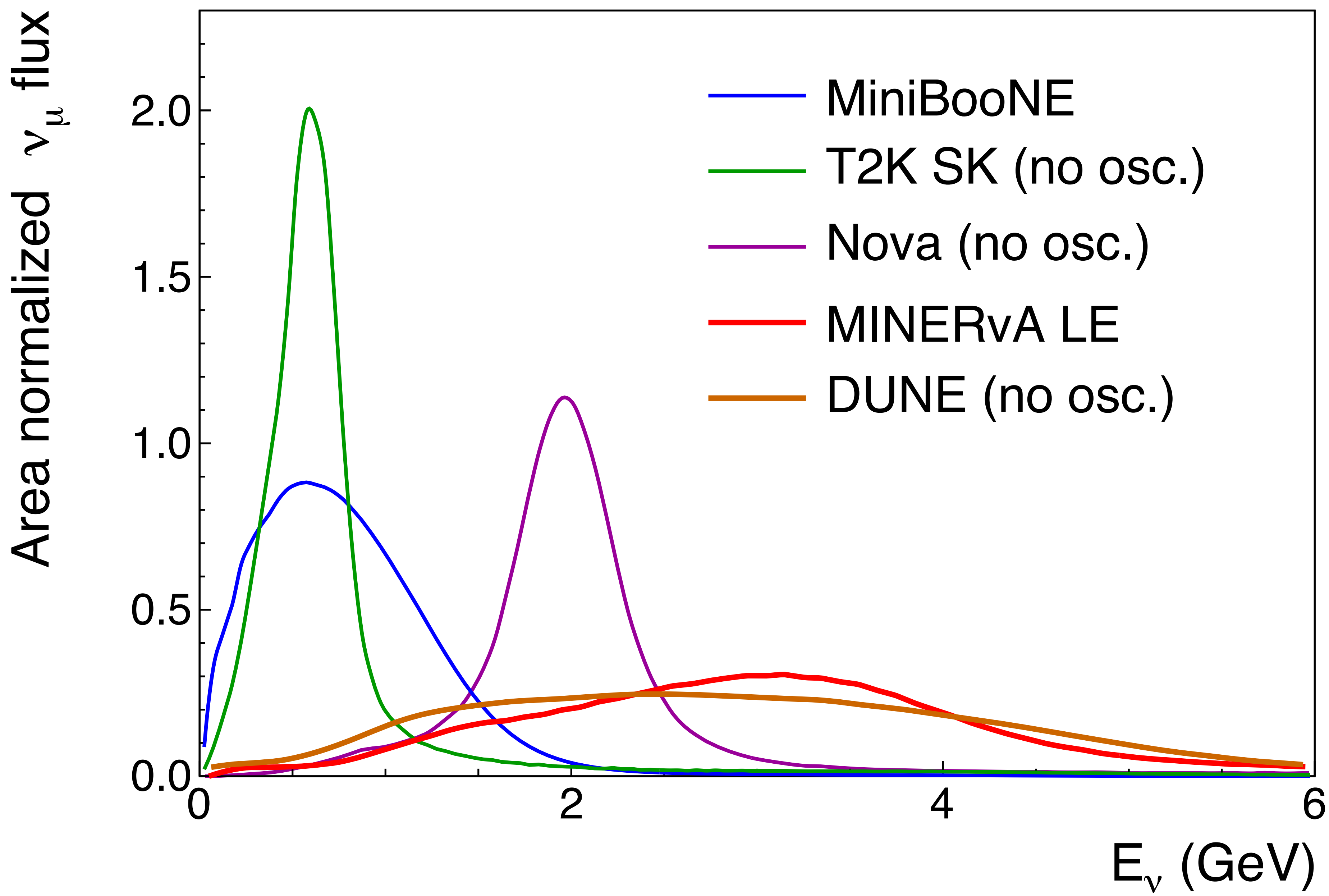






Fermilab

Neutrino Energies for Different Experiments

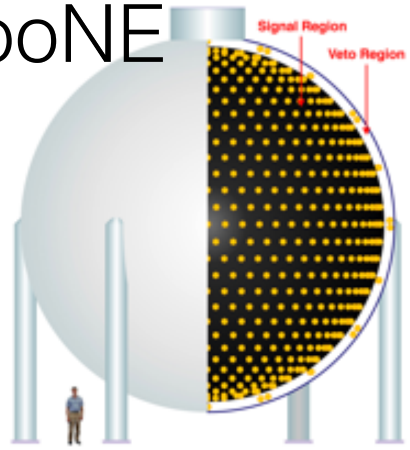


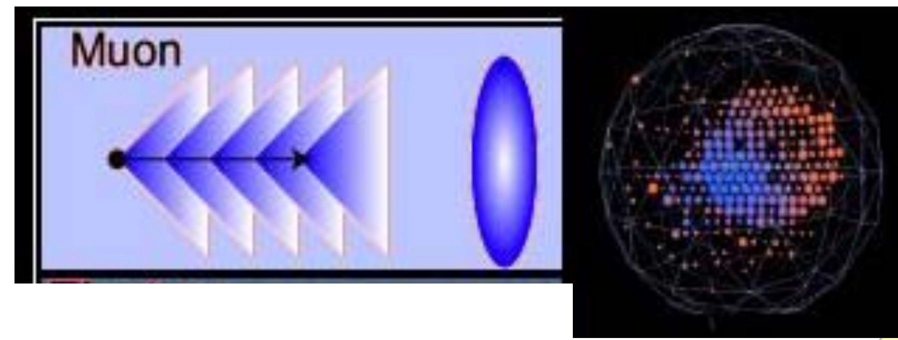
Plot courtesy of Phil Rodrigues

Fermilab

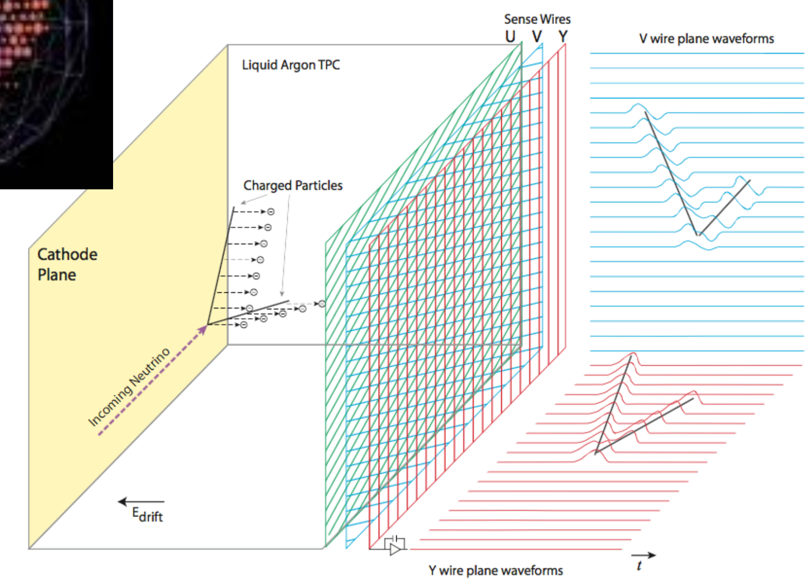
Examples of Different Detector Technologies

MiniBooNE

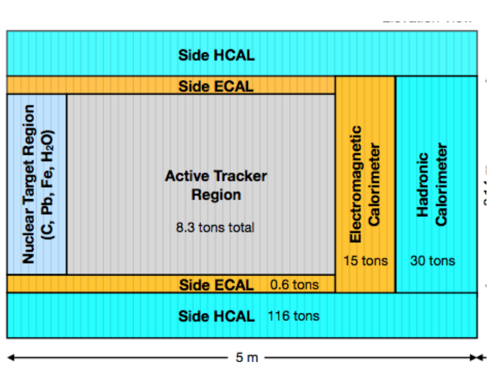


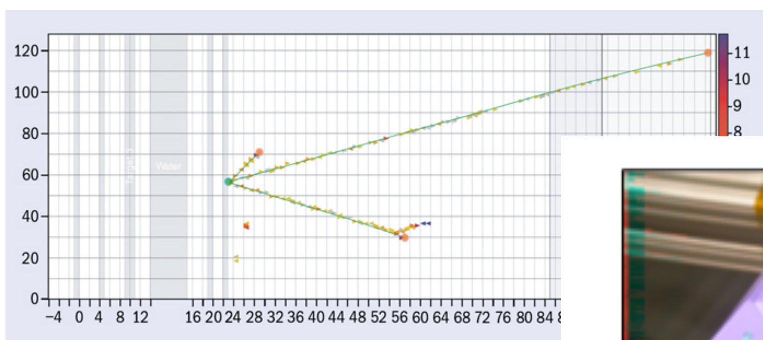


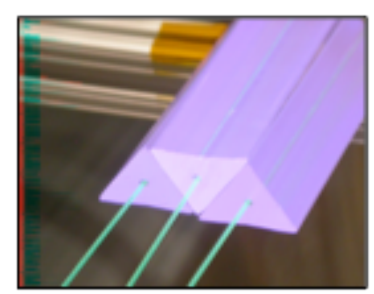
MicroBooNE



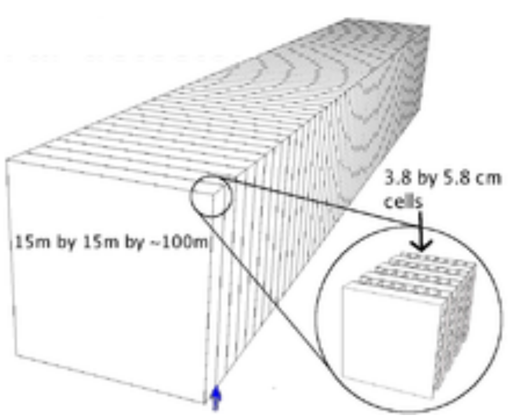
MINERvA

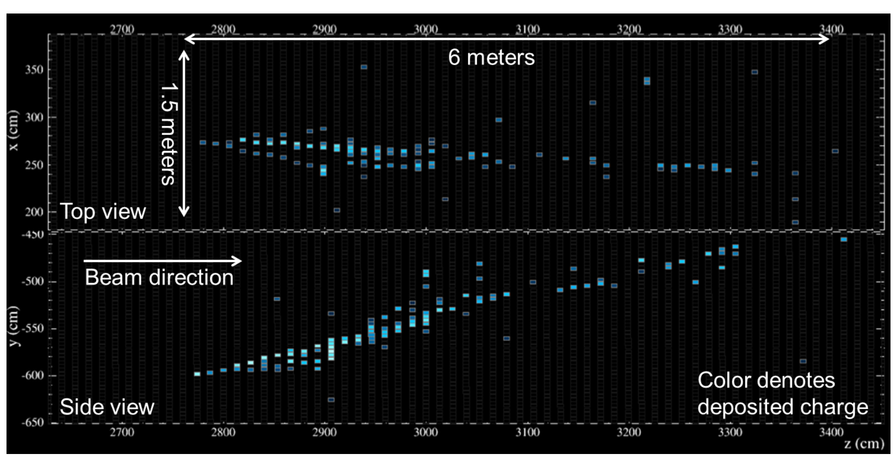


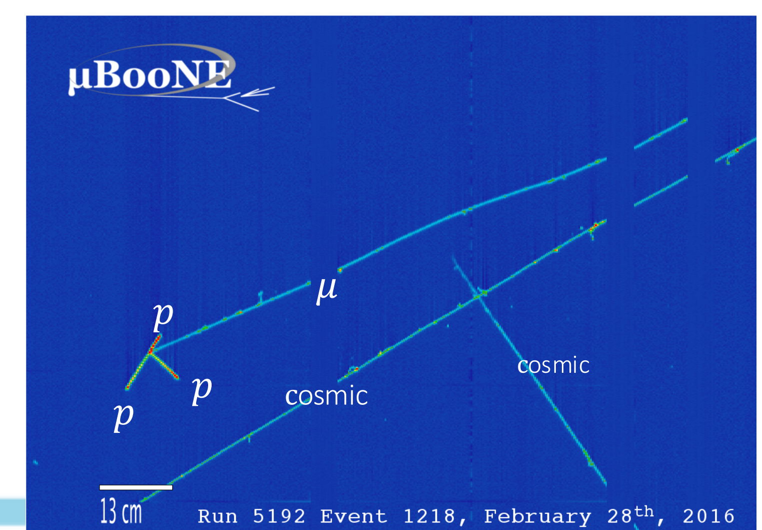




NOvA

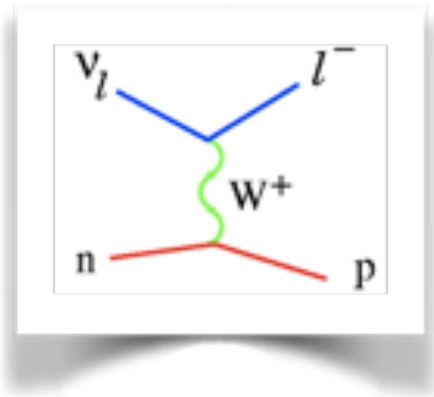




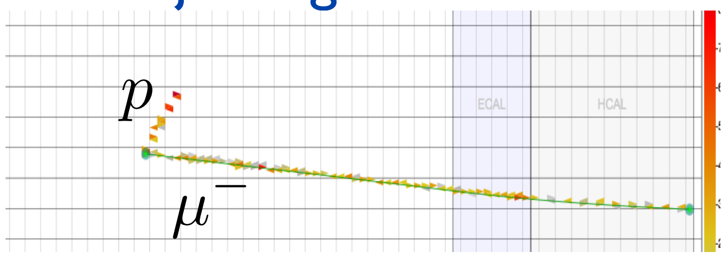


Charged Current Interactions

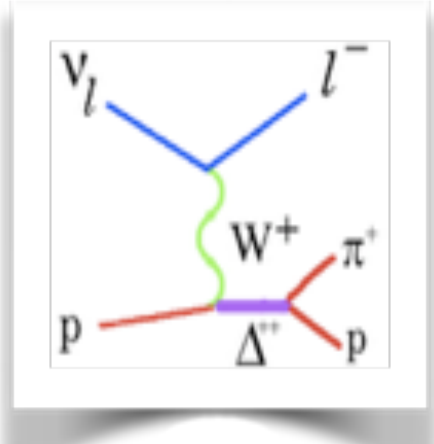
Quasi-elastic scattering (QE)



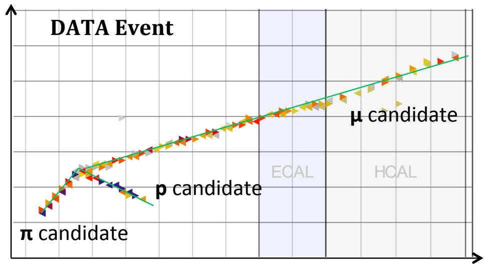
The neutrino scatters elastically off the nucleon ejecting a nucleon from the target



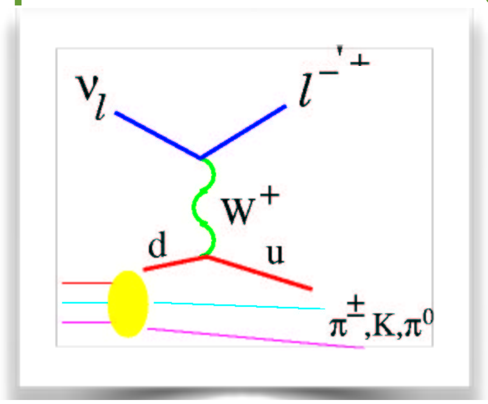
Resonance production (RES)



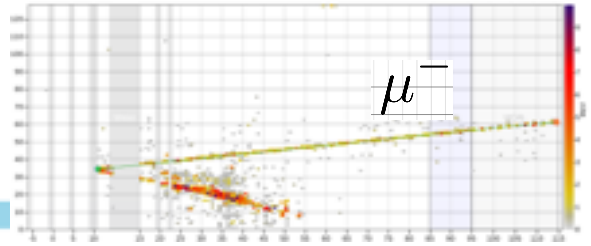
The neutrino can excite the target nucleon to a resonance state



Deep Inelastic scattering (DIS)

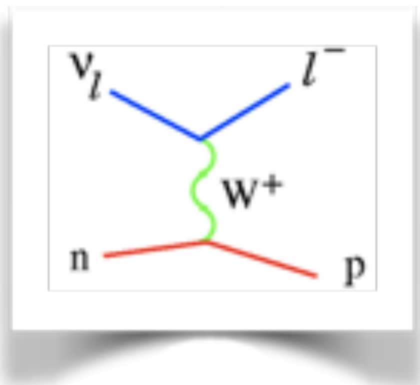


The neutrino scatters off a quark in the nucleon producing a hadronic system in the final state

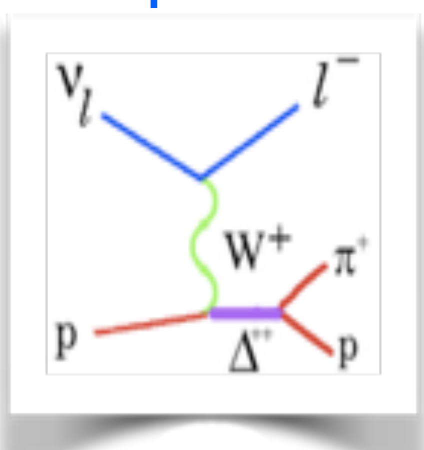


Charged Current Interactions

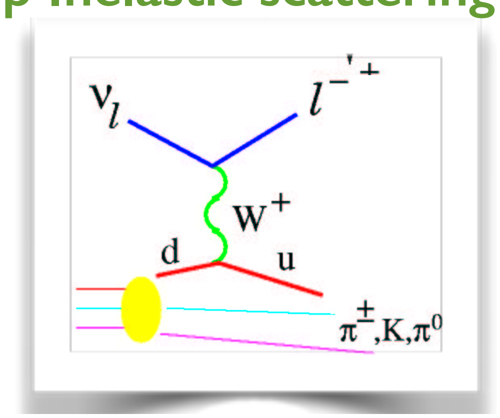
Quasi-elastic scattering (QE)

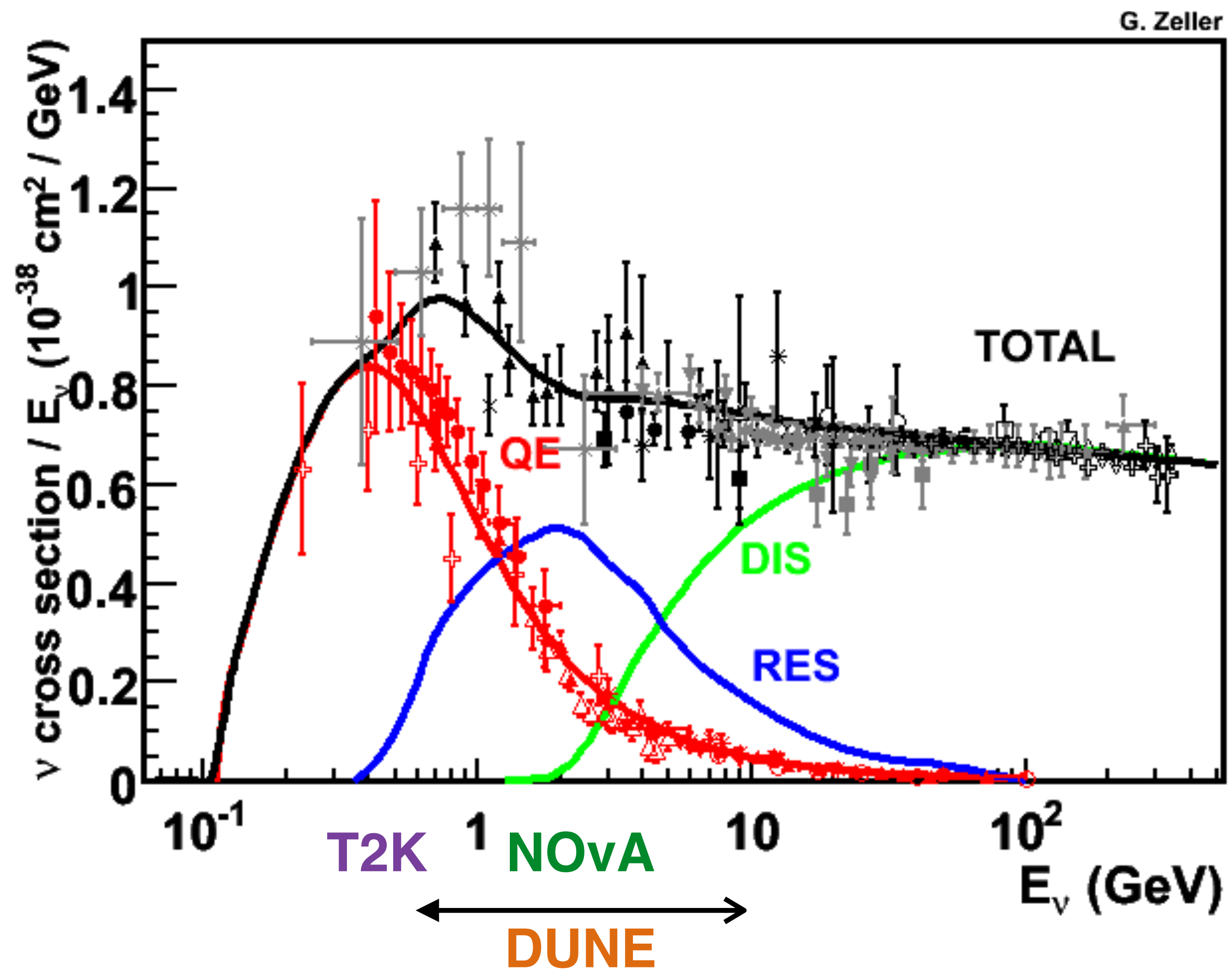


Resonance production (RES)



Deep Inelastic scattering (DIS)



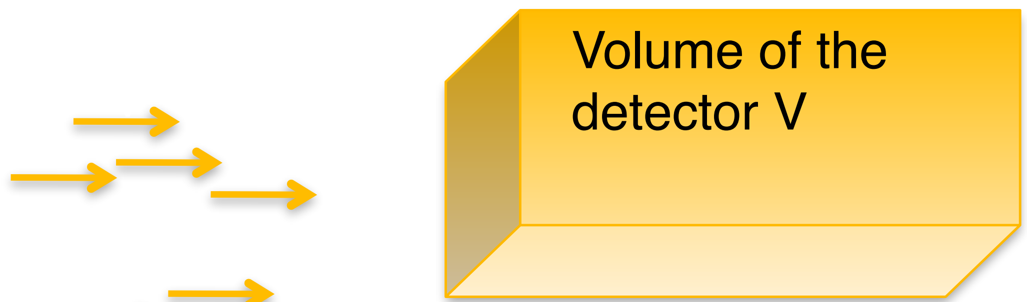


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Fermilab

Neutrino Cross Section

- What is the cross section?
  - A measure of the probability of an interaction occurring



Cross Section $$\sigma = \frac{N}{\phi T \epsilon}$$ Number of interactions that occurred

Total flux of incident neutrinos per unit area (ϕ)

Number of targets (T)

Neutrinos interact only by week force, at 1 GeV $\sigma(\nu N) \sim 10^{-38} cm^2$ → tiny

compare with $\sigma(pp) \sim 10^{-26} cm^2$

Cross Section is one of the largest systematics

PRL **116,** 181801 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

Measurement of Muon Antineutrino Oscillations with an Accelerator-Produced Off-Axis Beam

Cross section is one of the largest systematic uncertainties for oscillation experiments like T2K as an example

TABLE IV. Percentage change in the number of one-ring μ-like events before the oscillation fit from 1σ systematic parameter variations, assuming the oscillation parameters listed in Table III and that the antineutrino and neutrino oscillation parameters are identical.

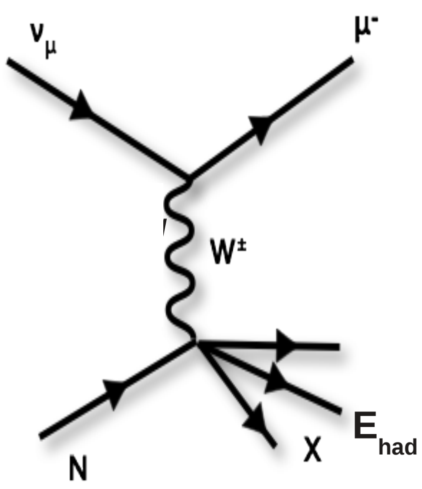
Source of uncertainty (number of parameters)	$\delta n_{\mathrm{SK}}^{\mathrm{exp}}/n_{\mathrm{SK}}^{\mathrm{exp}}$ (%)
ND280-unconstrained cross section (6)	10.0
Flux and ND280-constrained cross section (31)	3.4
Super-Kamiokande detector systematics (6)	3.8
Pion FSI and reinteractions (6)	2.1
Total (49)	11.6

T2K's uncertainties, from PRL 116, 181801 (2016)

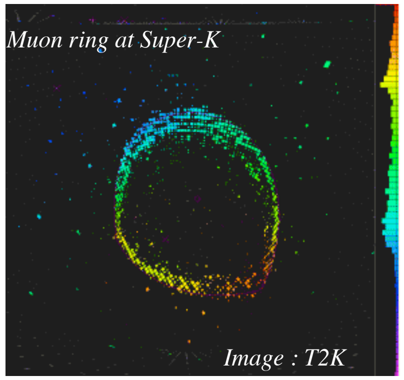
In More Detail

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

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

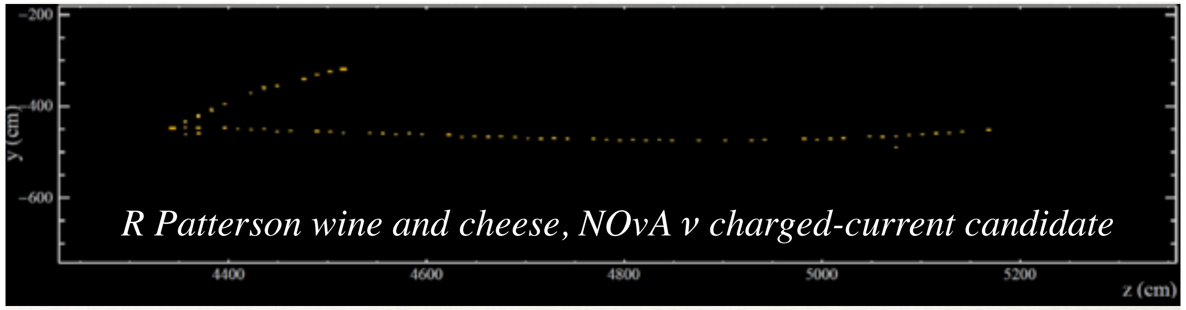


- Neutrino energy reconstruction is obtained using the final state particles
  - Cherenkov experiments use muon information



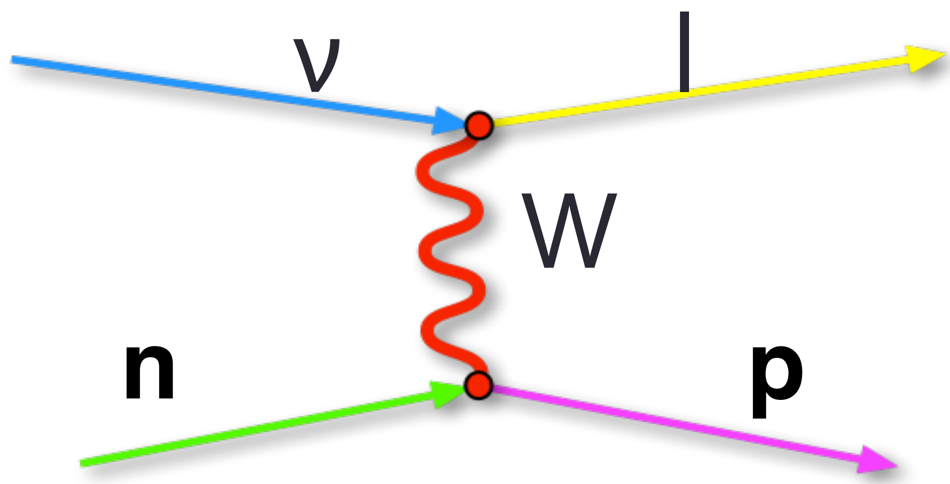
$$E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

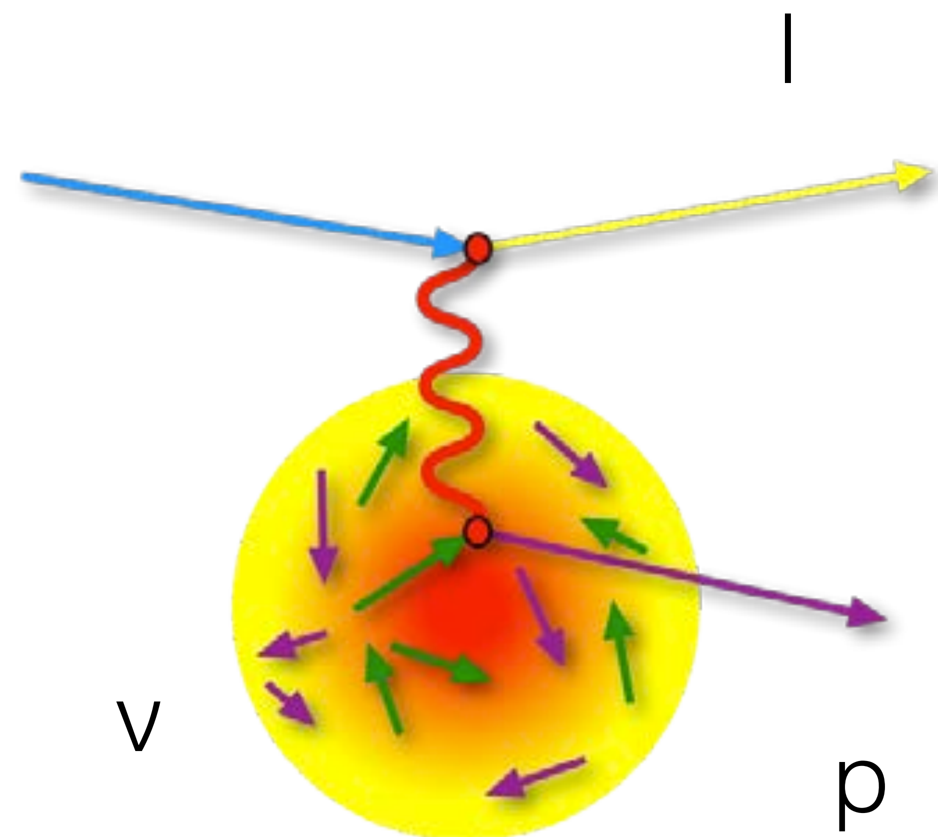
  - Fully active experiments reconstruct the energy using: $E_\nu = E_{lepton} + hadron$



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

Neutrino Interactions

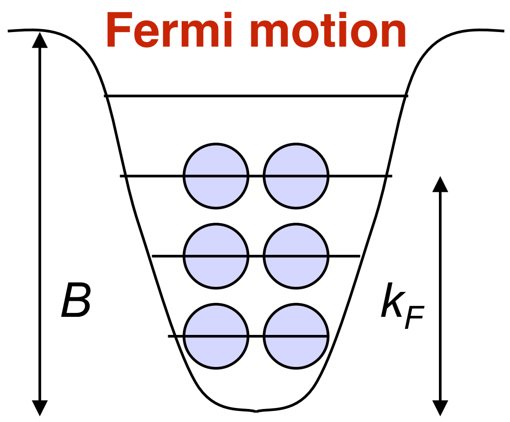




- We do not know:
  - Initial state bound nucleon momenta
  - Bound nucleon cross section
  - Multi-nucleon correlated states
  - Final state interactions
- Several challenges from the theoretical model side and experimental side to understand neutrino interactions

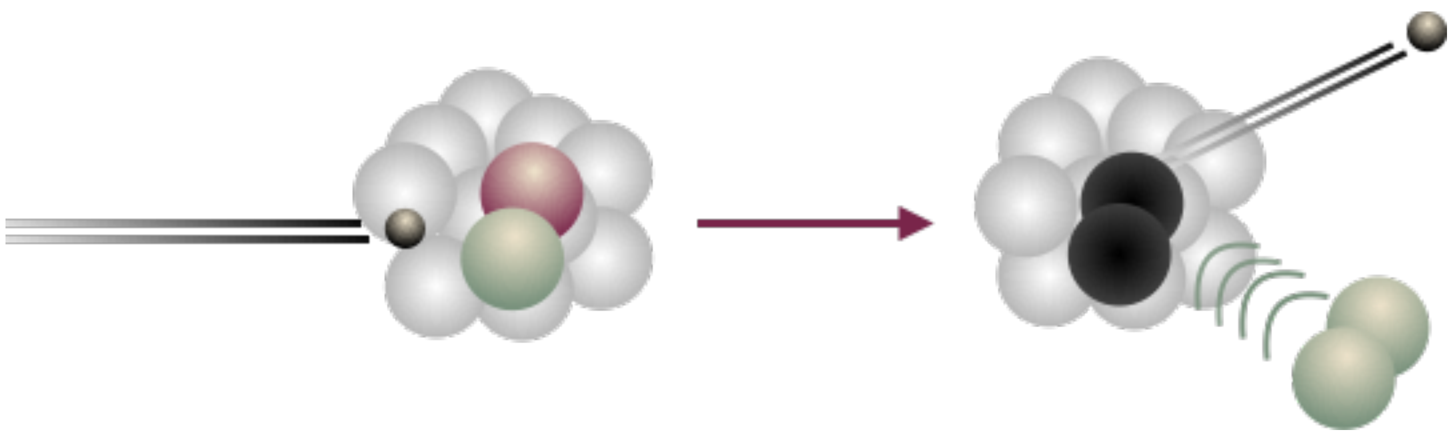
Nuclear Effects

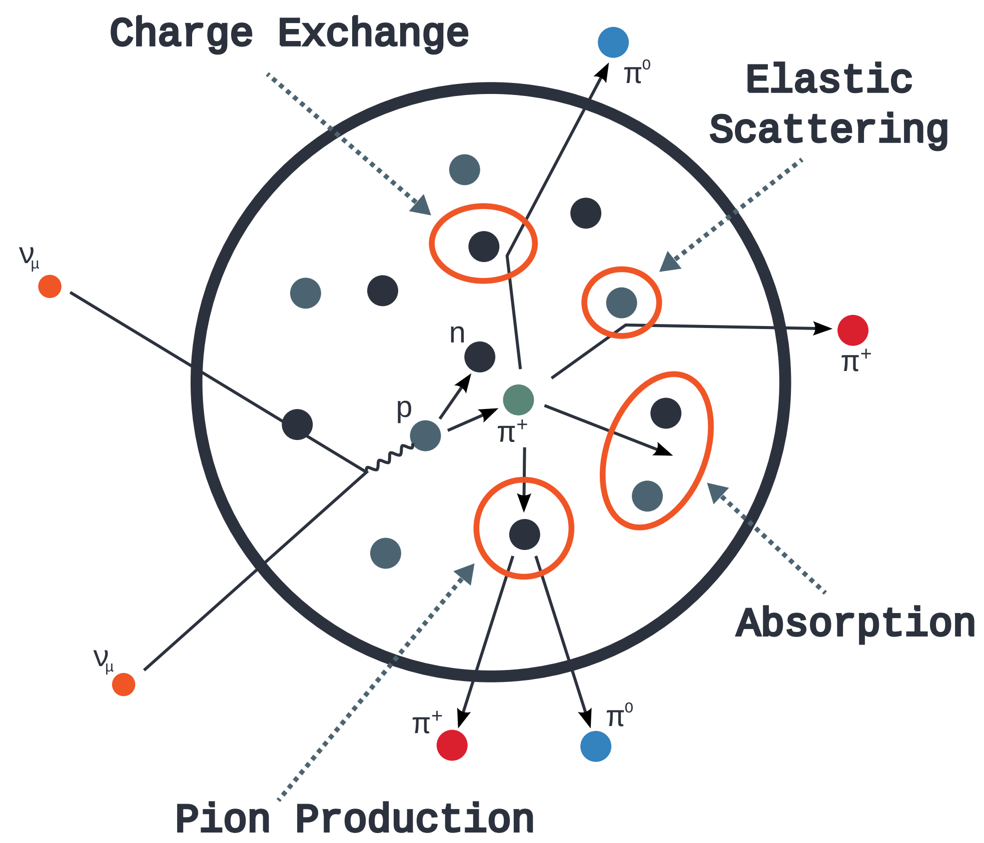
- Fermi motion: In a nucleus, the target nucleon has a momentum. Modeled as Fermi gas that fills up all available state until some Fermi momentum
- Pauli blocking: Pauli exclusion principle ensures that states cannot occupy states that are already filled
- Multi nucleon interactions
- Final state interactions



Final State Interactions (FSI)

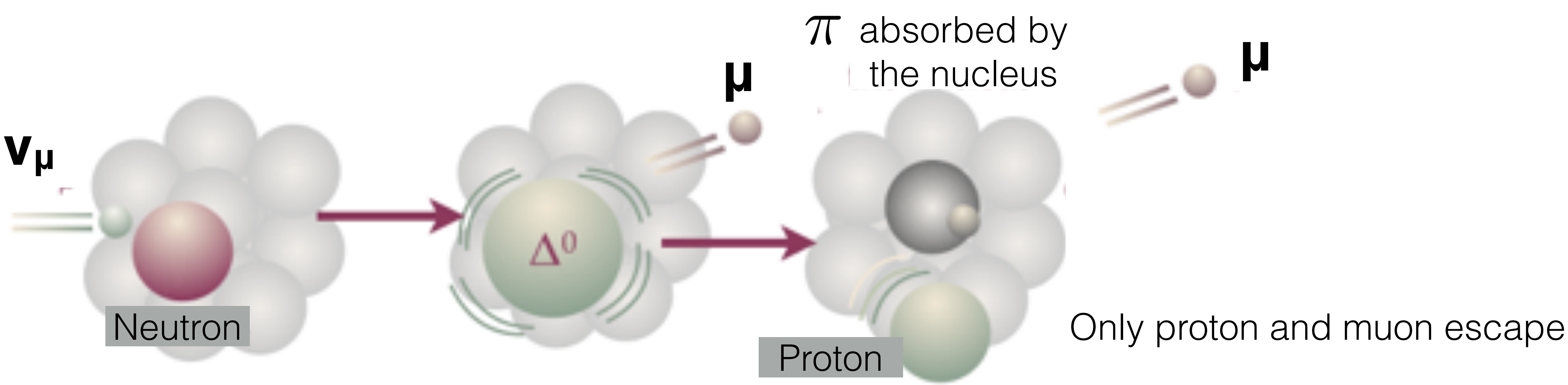
Multi nucleon interactions





Example of Nuclear Effects (Final State Interaction)

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

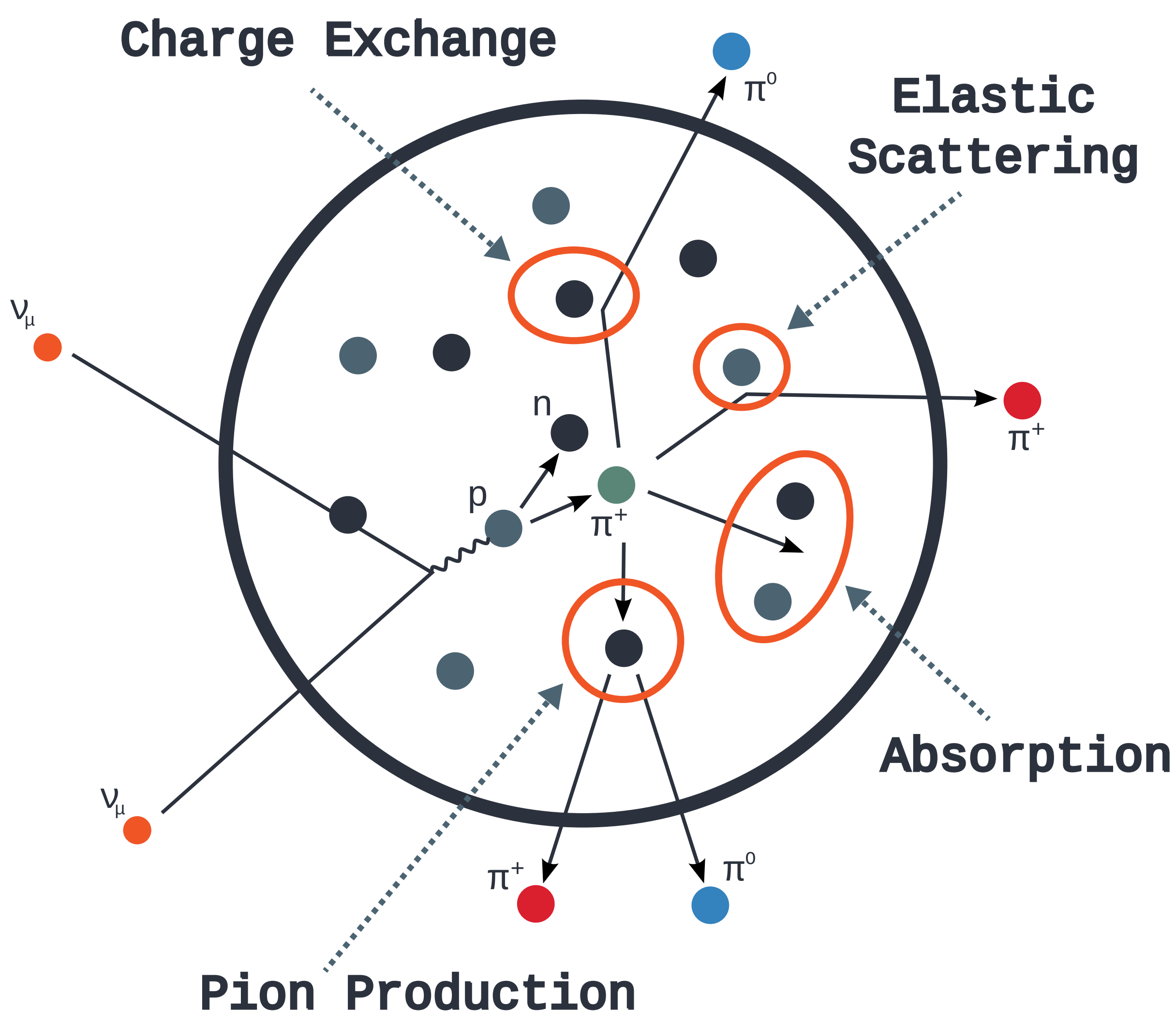


Start as a RES interaction, the pion is absorbed and the interaction looks QE like in our detector

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- Pion absorption is twice as big in Argon as it is in Carbon!

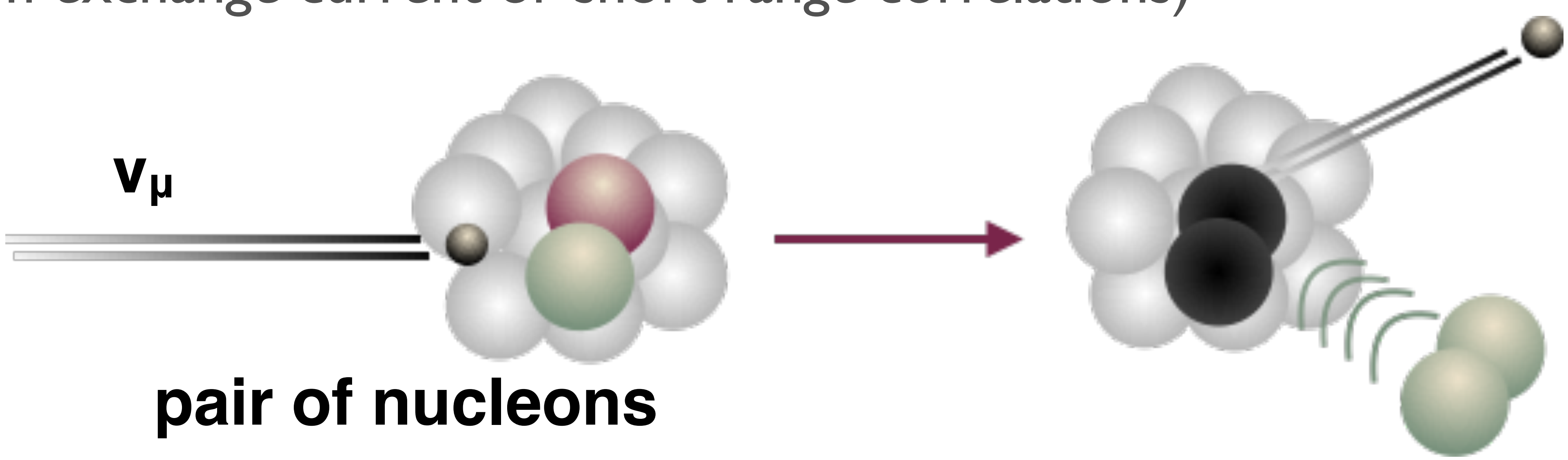
Example of Nuclear Effects (Final State Interactions)

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

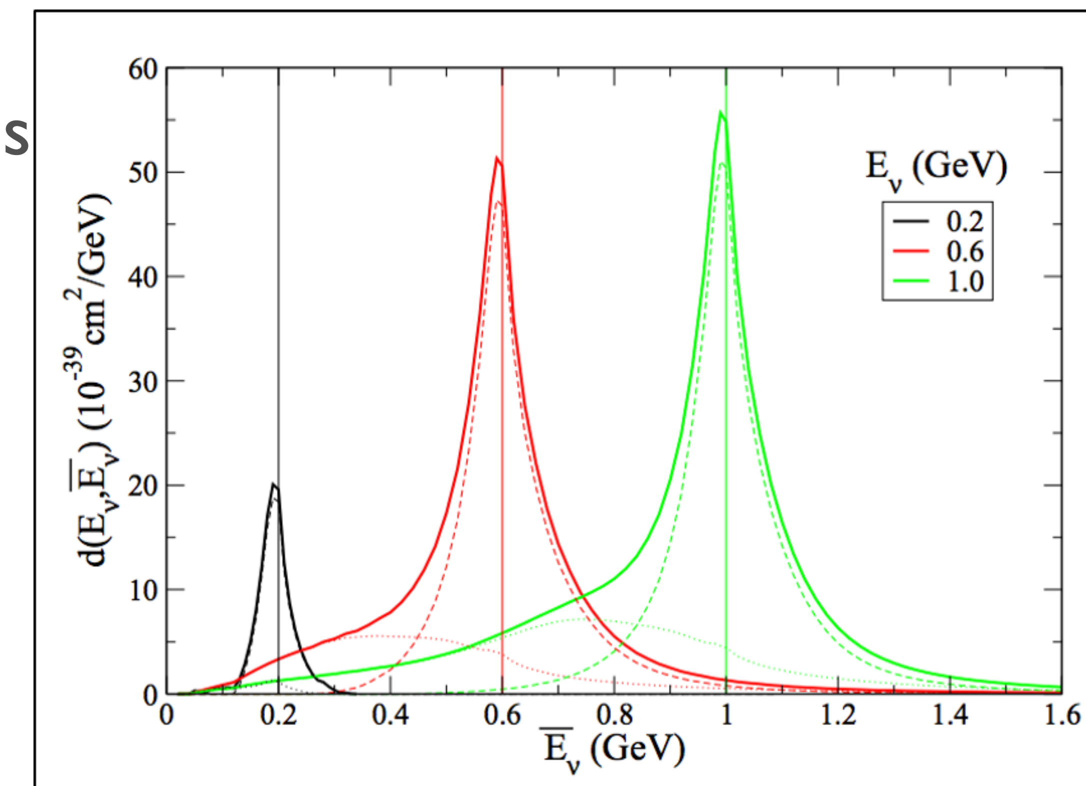


Example of Nuclear Effects (multi-nucleon interaction)[2p2h]

- Nuclear effects modify the neutrino energy, for example multi-nucleon interactions (Meson exchange current or short range correlations)



- The resulting di-nucleon pair undergoes final state interaction and produce low energy protons and neutrons which we do not detect well
- Multi-nucleon processes smear the reconstructed neutrino energy
- Solid lines: multi nucleon contributions
- Dashed lines: genuine CCQE events

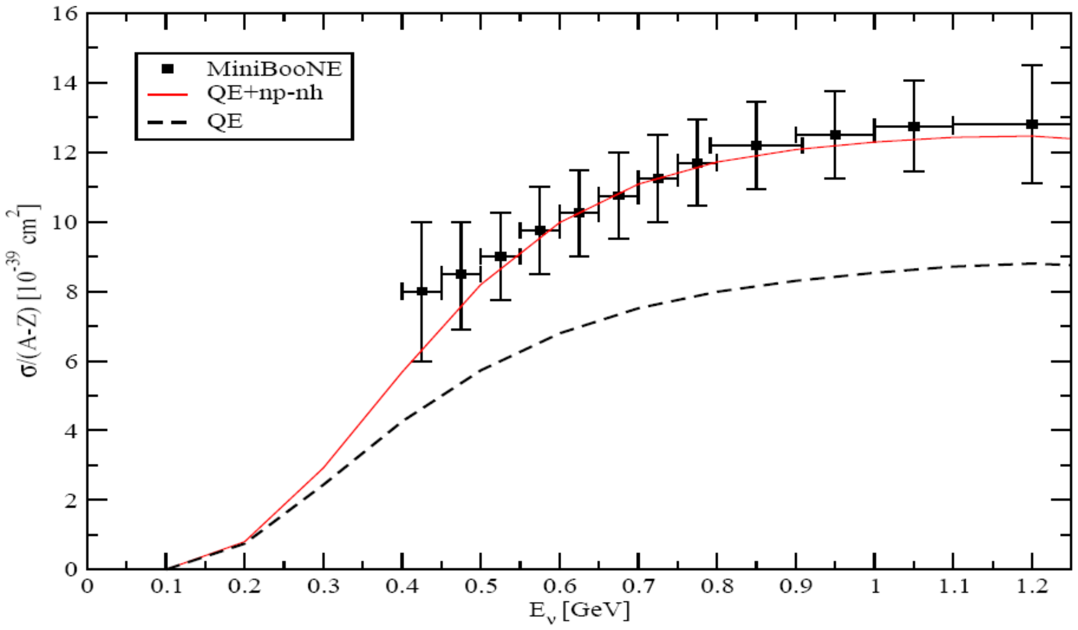


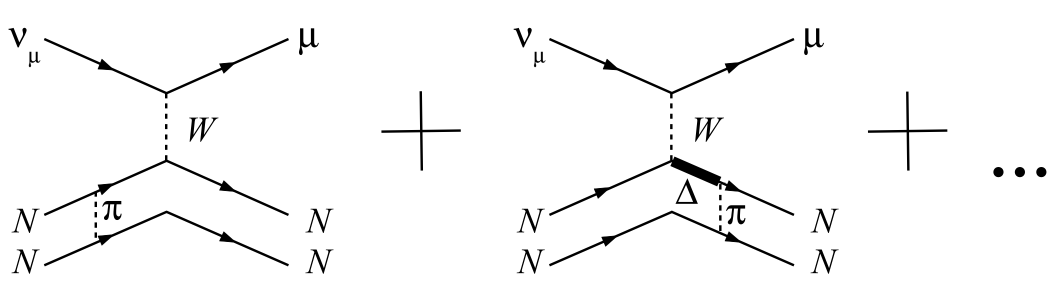
Martini et al. arXiv:1211.1523

Including 2p2h model

- Inclusion of the multi nucleon emission channel (np-nn) gives better agreement with data

Model compared to MiniBooNE data



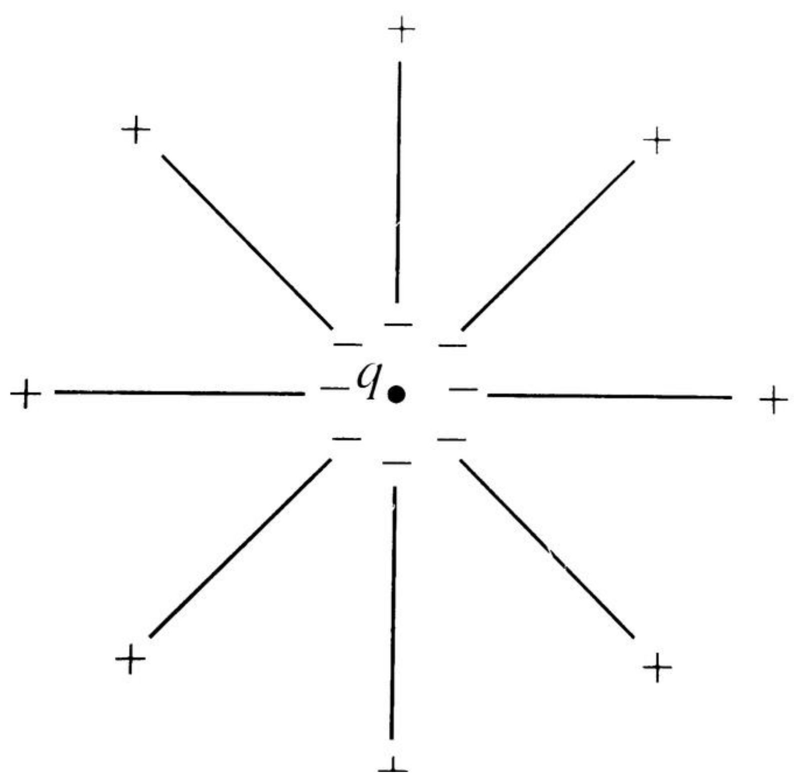


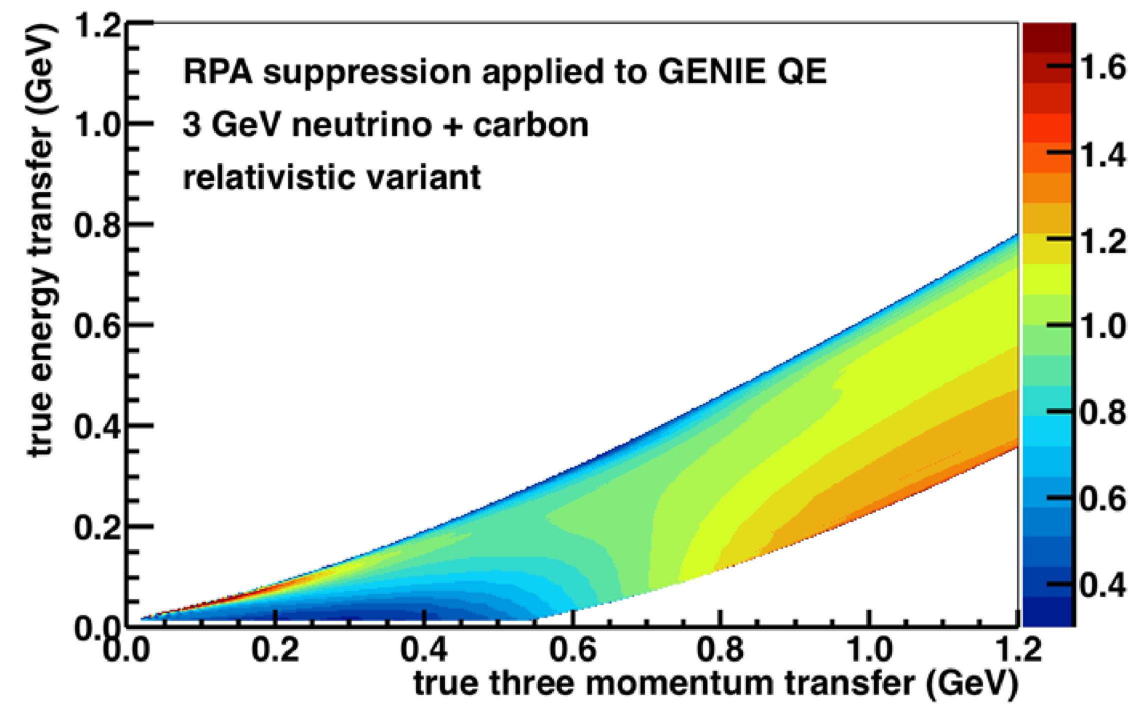
M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

- We are using one of the theoretical predictions and latest GENIE implementation of Valencia model for QE-like 2p2h, arXiv:1601.02038, PRC 70, 055503 (2004), PRC 83, 045501 (2011)

Including Random Phase Approximation (RPA)

- Analogous to screening of electric charge in a dielectric
- For neutrino scattering in a nucleus, imagine the W as having a weak charge and polarizing the nuclear medium
- Calculated using Random phase approximation (RPA), PRC 70, 055503 (2004)
- We add the RPA to GENIE by reweighting the QE events
- Suppress cross sections at low four momentum transfer Q^2

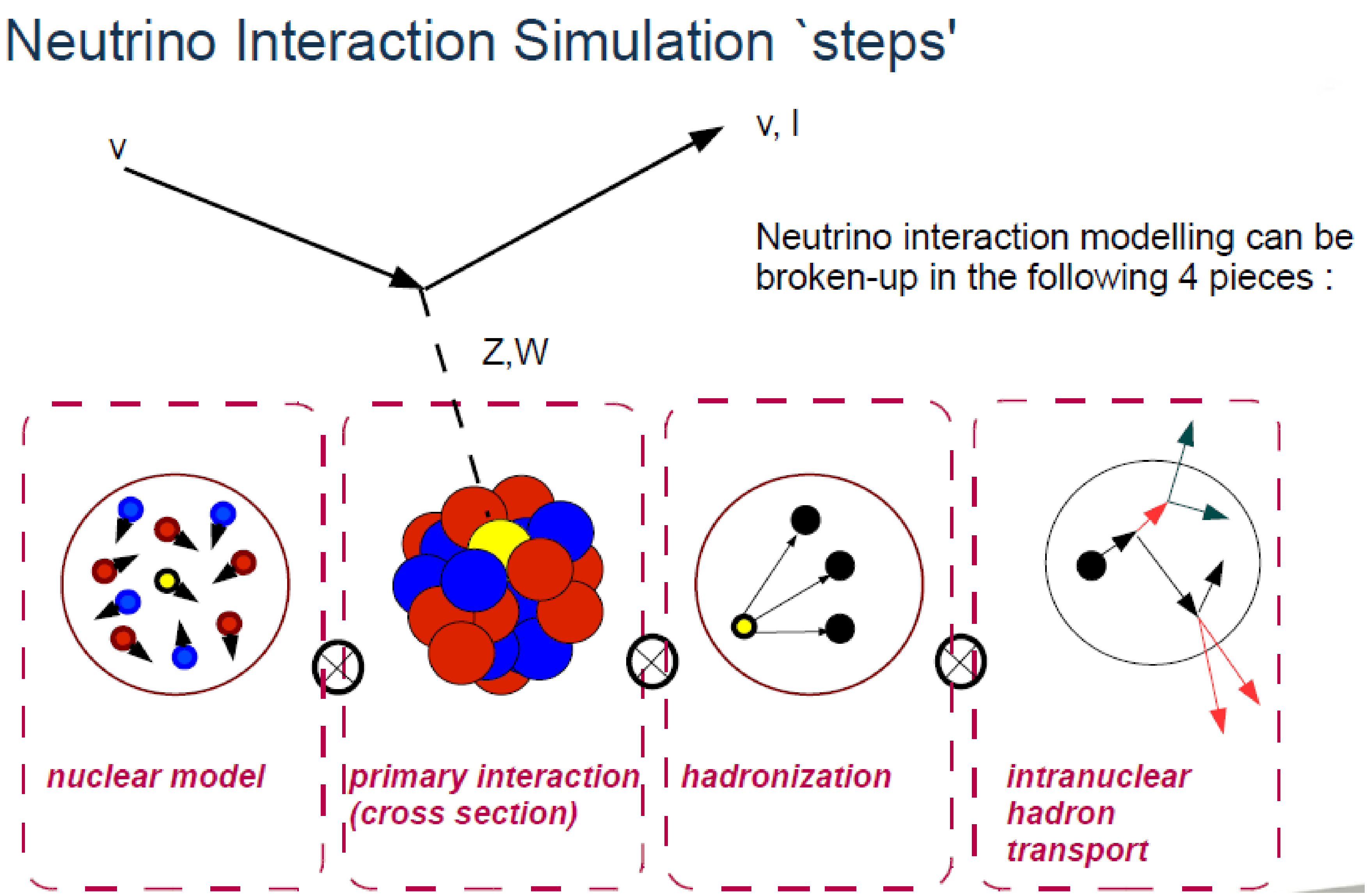




Simulations

- We use Monte Carlo simulations (GENIE) for the analysis

GENIE



Costas Andreopoulos, *Rutherford Appleton Lab.*

Fermilab

Simulations

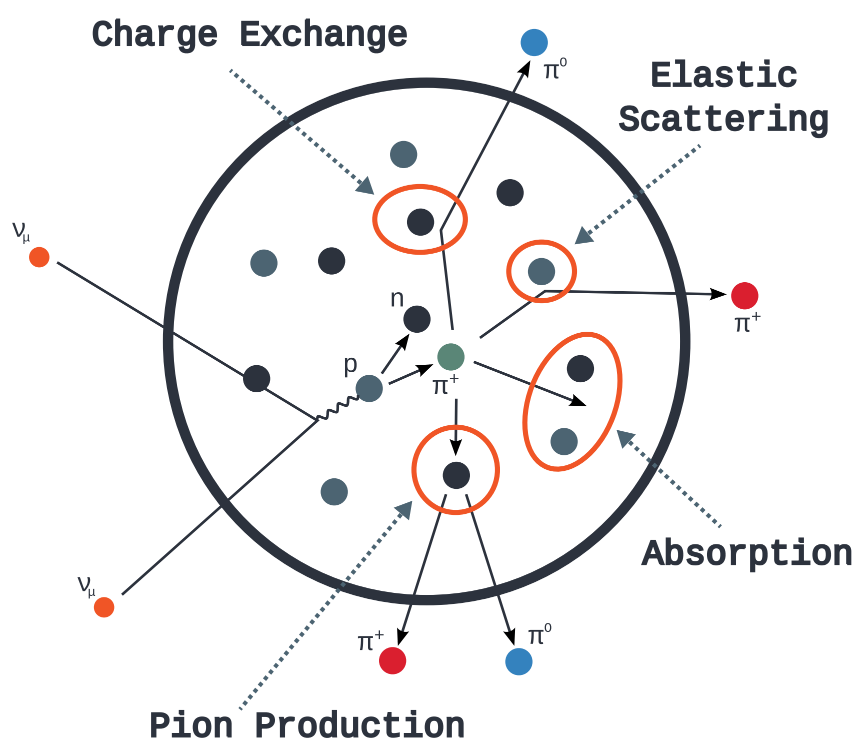
- We have made considerable progress in modeling neutrino interactions lately
- We use GENIE (2.8.4) Monte Carlo generator
- For detector response we use GEANT4 (4.9.2)
- Quasi-elastic scattering from nuclei is simulated using:
  - Relativistic Fermi Gas model with Bodek-Ritchie tail
  - Using the old dipole axial form factor assumption and axial mass M_A=0.99 GeV
    - We still need to update to the latest model independent axial form factor "z-Expansion" tuned with deuterium data, Phys. Rev. D93 (2016), 113015
  - Fermi momentum k_f=221 MeV
  - BBBA05 model for vector form factors
  - Final state interaction simulation

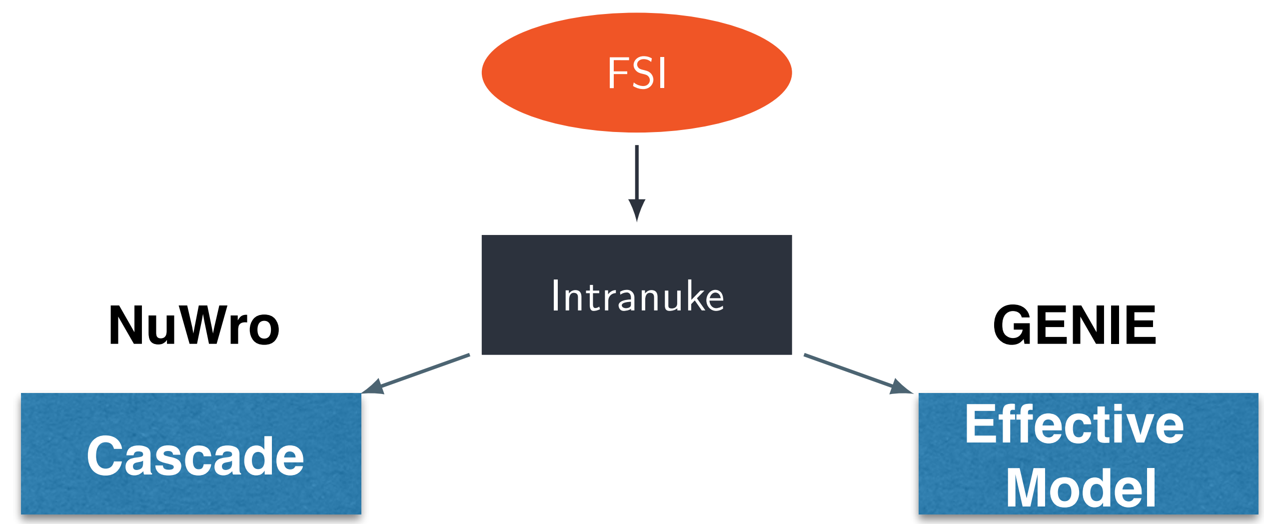
GENIE

Fermilab

Final State Interaction Model (FSI)

- Final state interactions are very important; they modify the particles coming from the initial interaction before they leave from the nucleus





NuWro – Cascade

- intranuclear cascade
- data-driven cross sections
- Oset model for pions (coming soon)

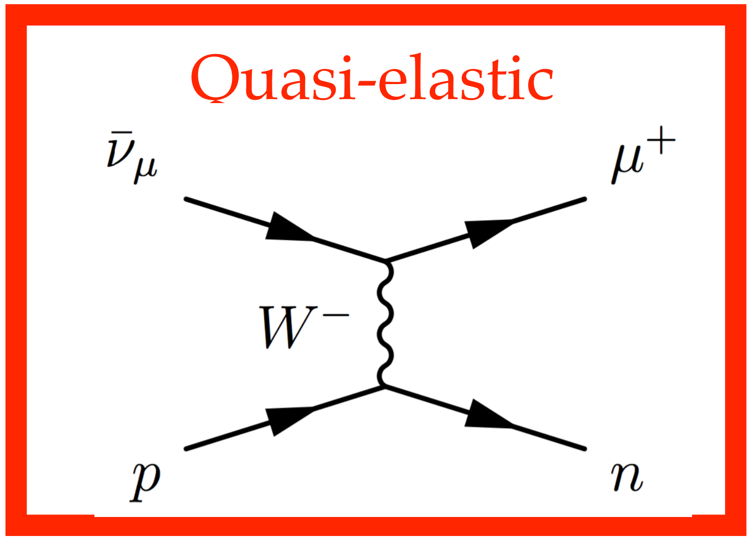
GENIE – Effective Model

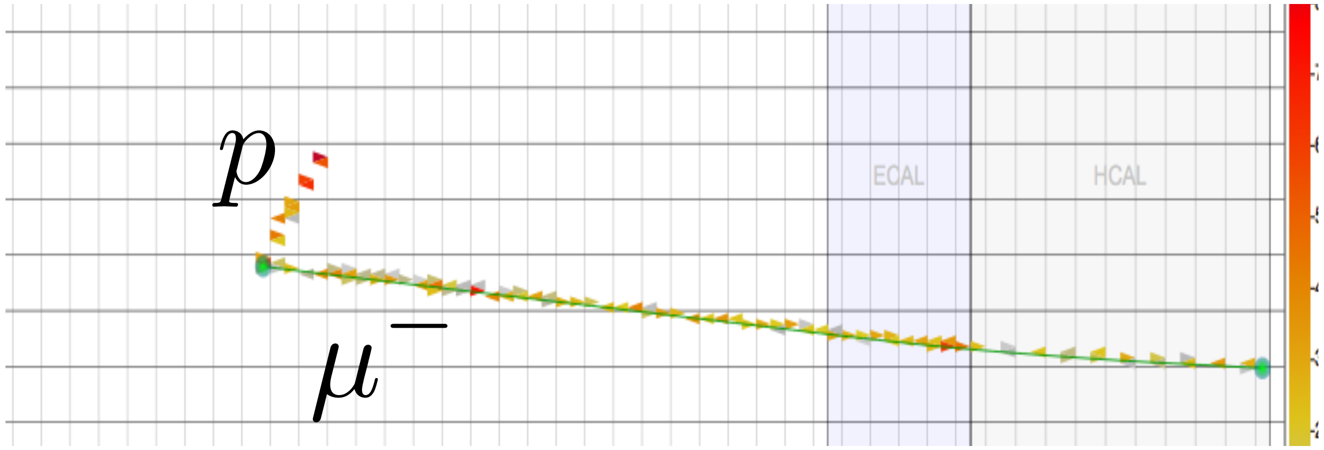
- INC-like with one "effective" interaction
- tuned do hadron-nucleus data
- easy to reweight

courtesy of Tomasz Golan

- We are using the default GENIE's effective FSI model

Quasi-Elastic Scattering





Fermilab

Quasi-Elastic Scattering (CCQE)

- Using Llewellyn-Smith formalism:

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

- A, B and C are functions F1, F2 and the axial-vector FA

$$\begin{aligned}
A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\Big\{&(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2\\
&+\frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2\\
&-\frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\}
\end{aligned}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3)\right]$$

$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

Fermilab

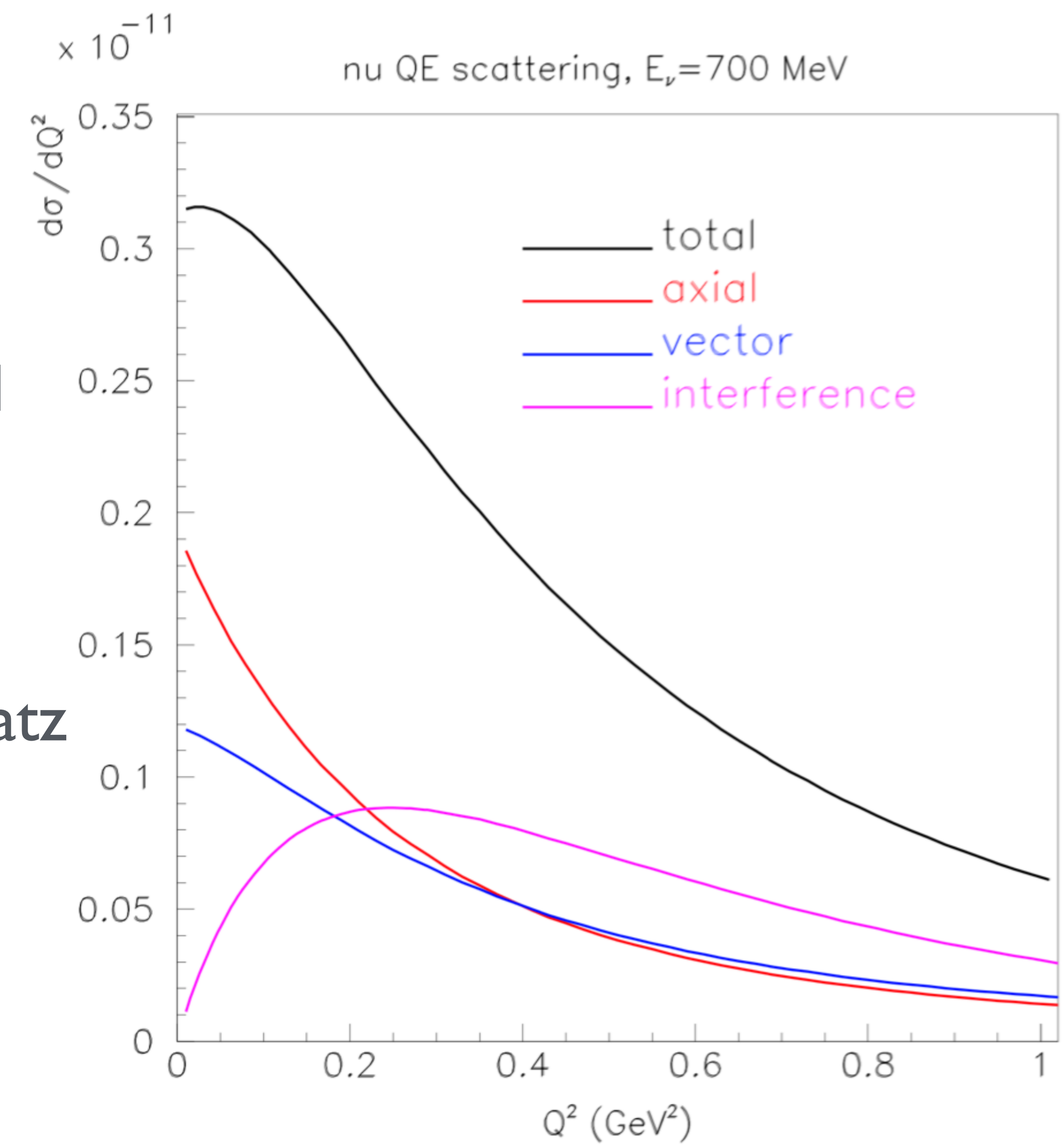
Quasi-Elastic Scattering (CCQE)

- 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

Fermilab

Axial Form Factor

- The dipole axial form factor ansatz:

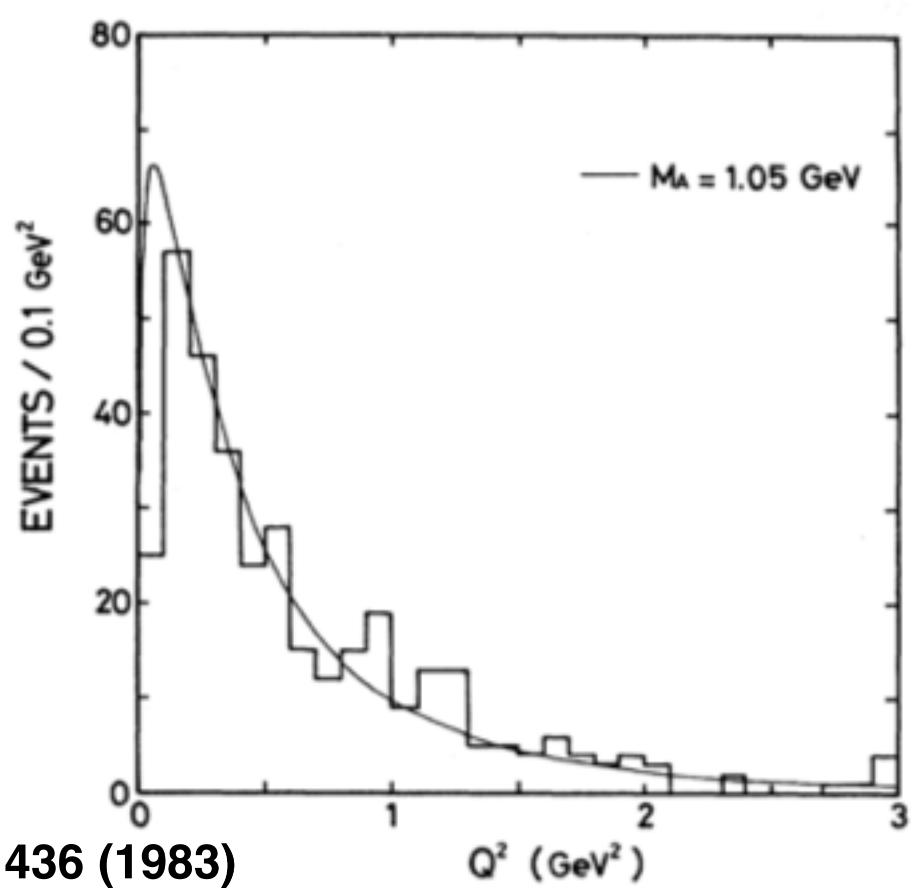
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

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

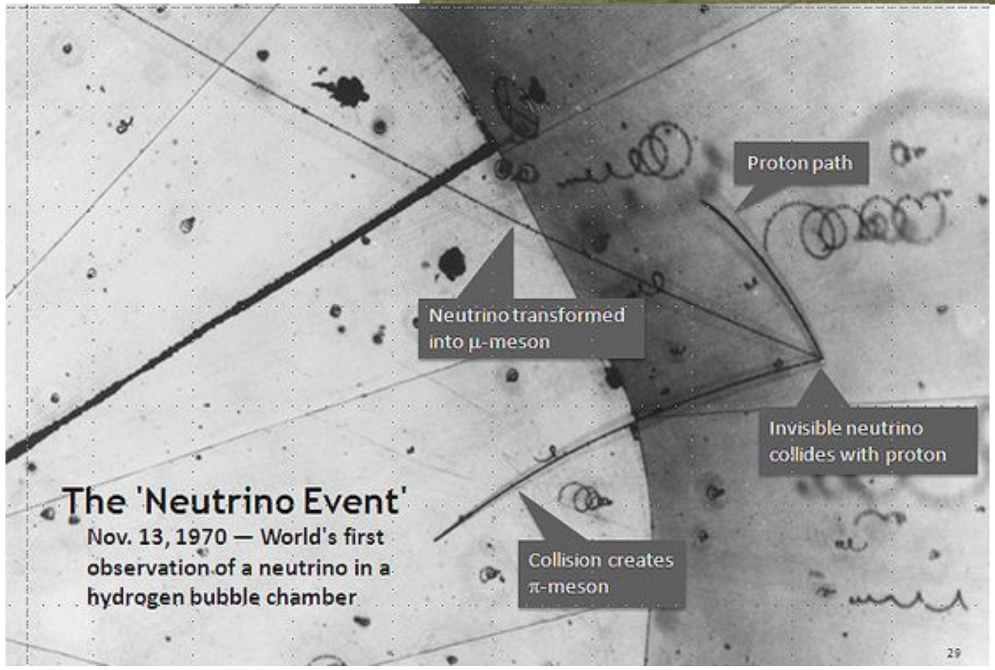
Bubble chamber experiment at Fermilab

$$M_A = 1.014 \pm 0.014 GeV$$

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



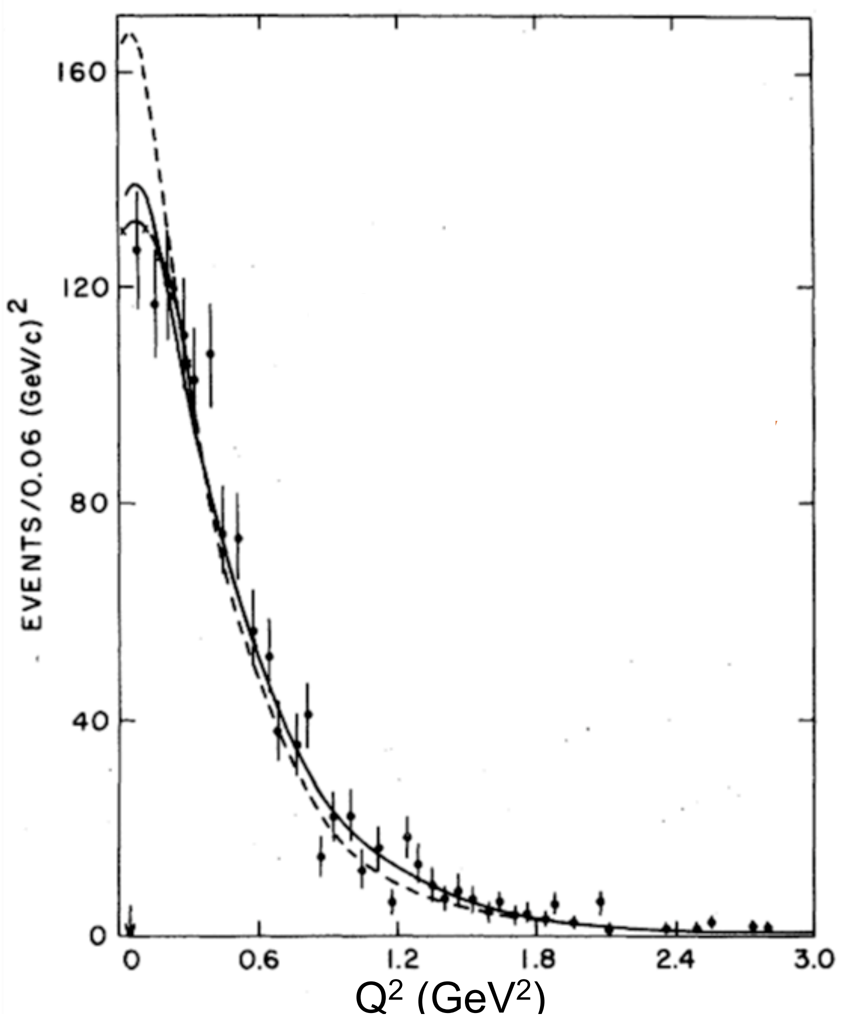
Kitagaki, PRD 28, 436 (1983)



Axial Form Factor

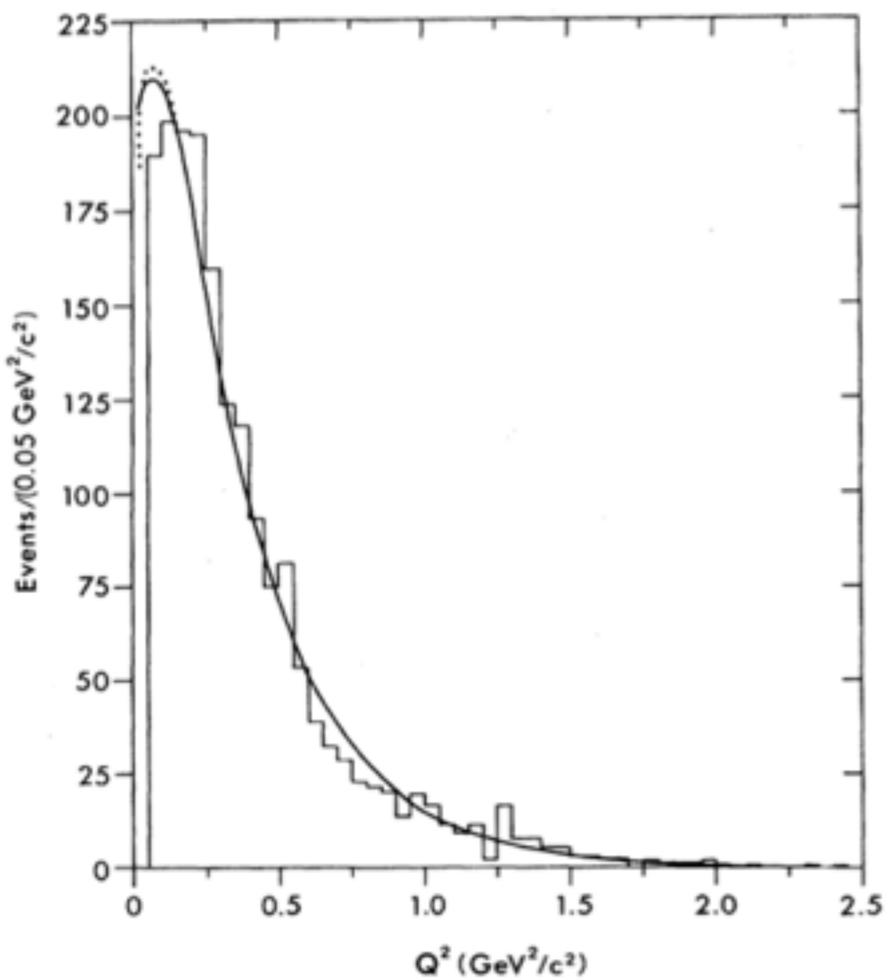
- These experiments measured the axial mass Ma, pretty good agreement between the experiments

$M_A = 1.07 \pm 0.06 GeV$



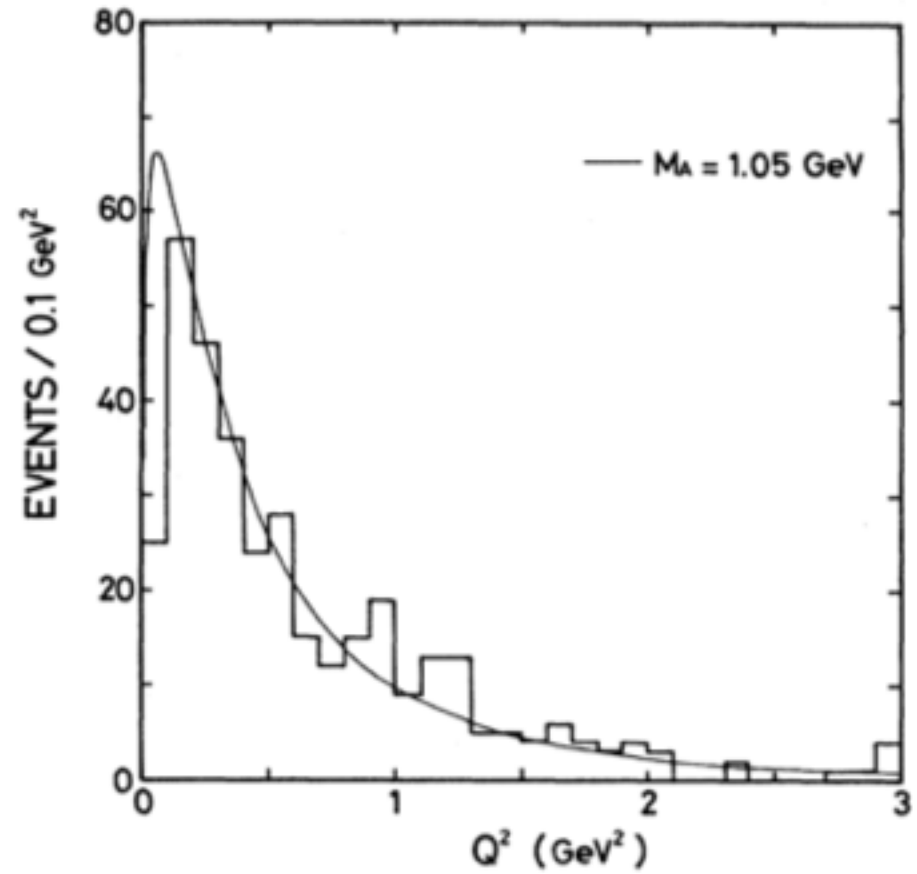
Baker, PRD 23, 2499 (1981)

$M_A = 1.00 \pm 0.05 GeV$



Miller, PRD 26, 537 (1982)

$M_A = 1.05 \pm 0.16 GeV$



Kitagaki, PRD 28, 436 (1983)

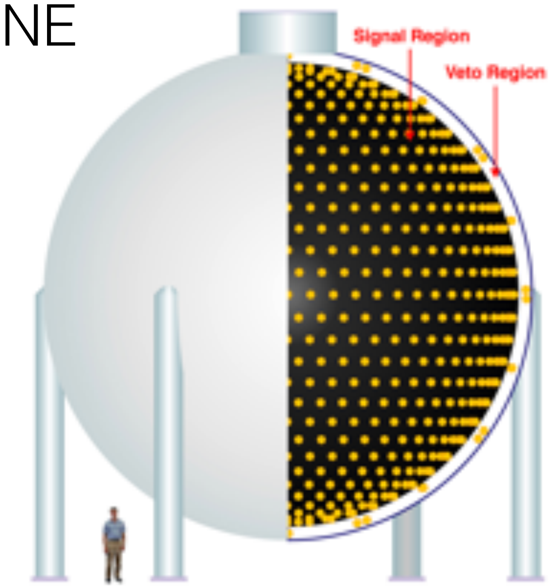
Fermilab

Axial Form Factor

- The dipole axial form factor ansatz:

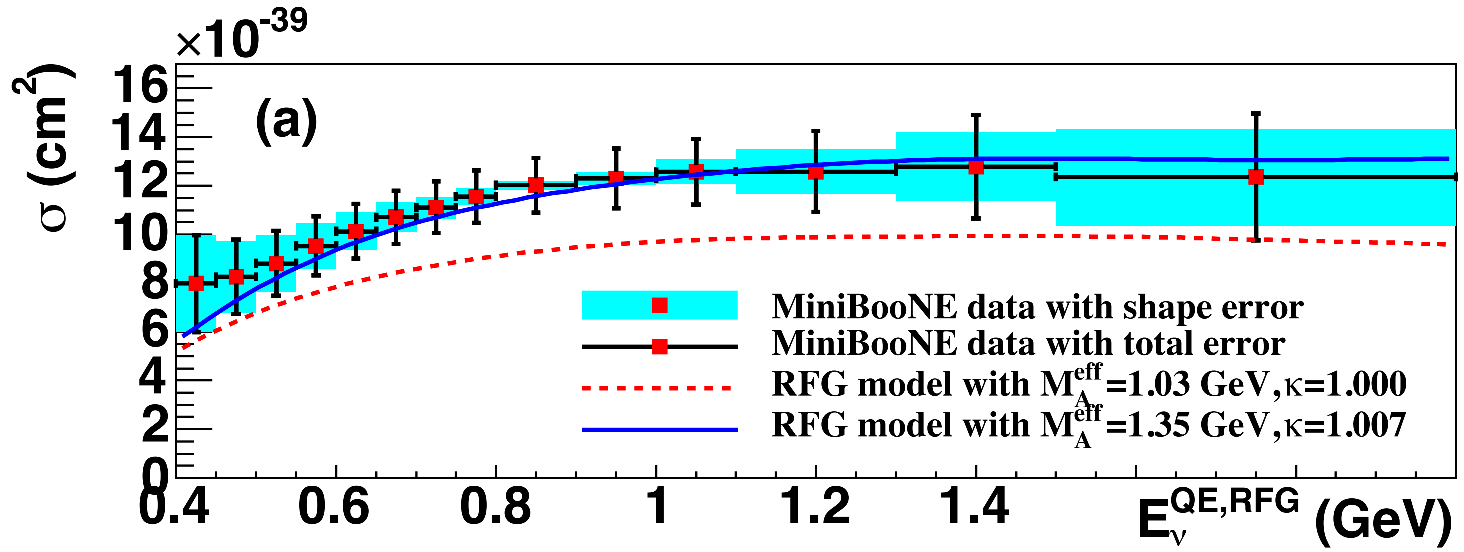
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

MiniBooNE



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

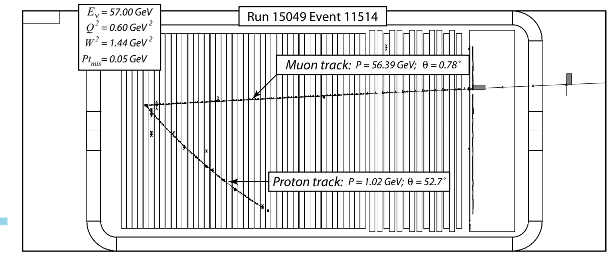
$$M_A = 1.35 \pm 0.17 GeV$$

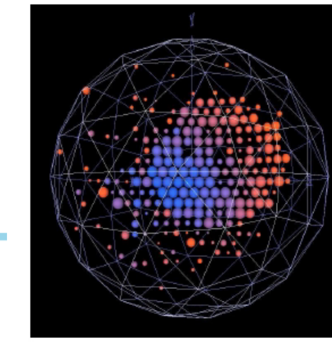


- Other experiments such as K2K, SciBar and MINOS find similar higher axial mass compared with the world average

Fermilab

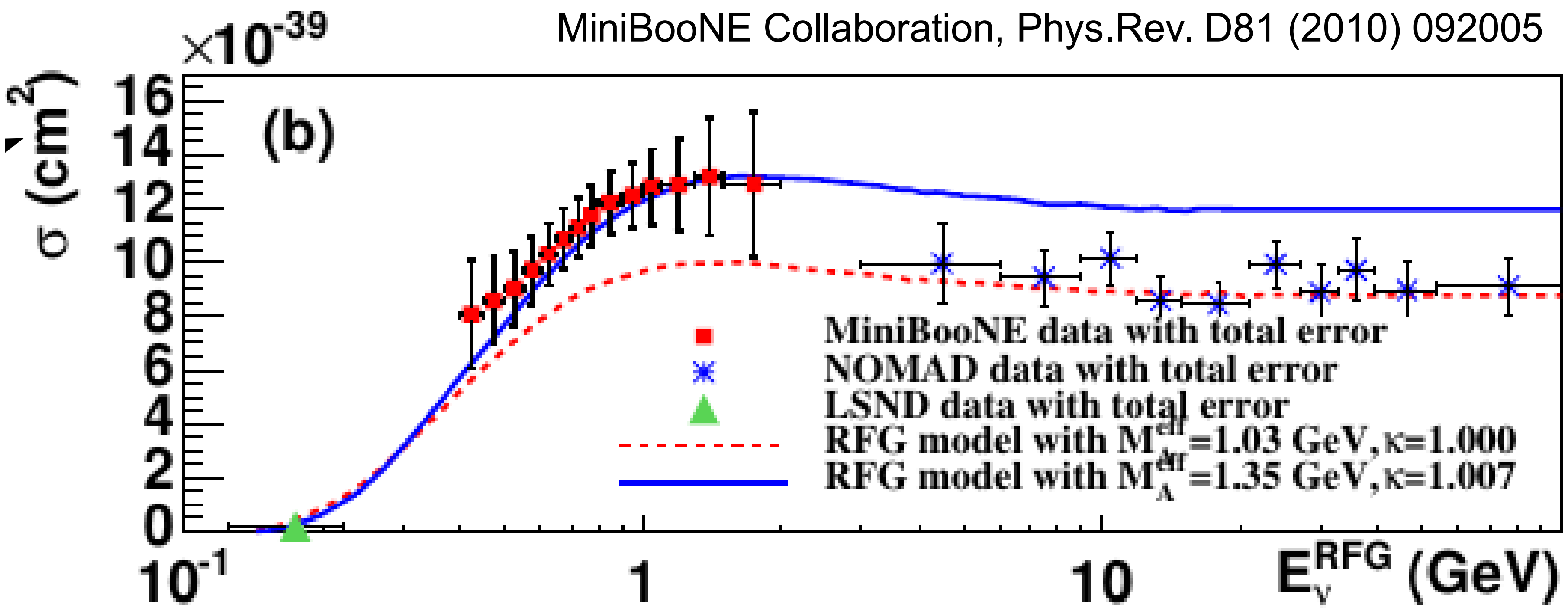
Modern CCQE Data





- Some examples of modern experiments:
  - NOMAD experiment uses carbon as a target and a tracker detector with high energy experiment <E>=24 GeV, 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>=0.8 GeV, analysis used ν_μ CC with no pions (purity 77%). Signal definition: event with no pions

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

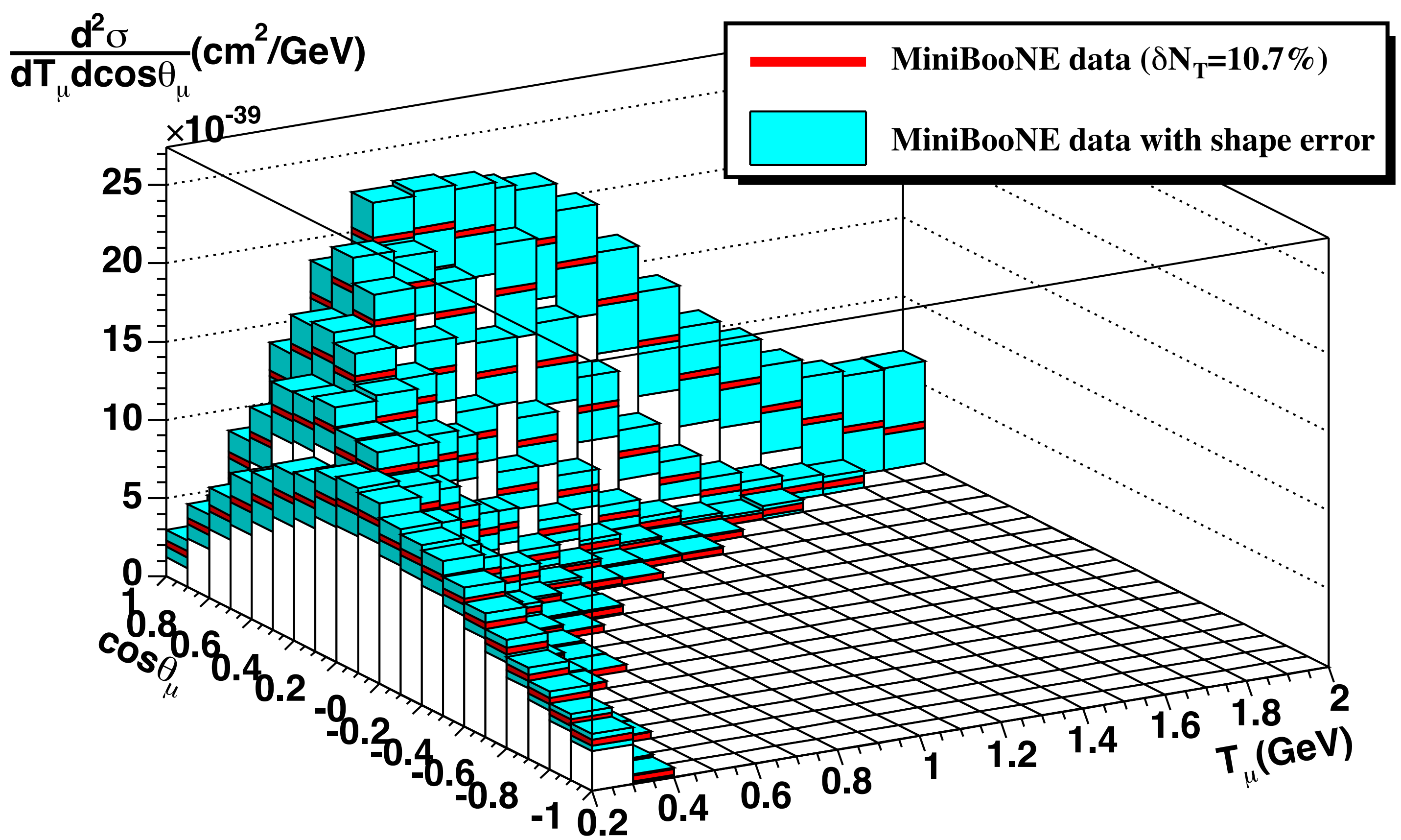
puzzle?

- **This high mA is an effective parameter that we expect represents multi-nucleons effects, and not directly the form factor itself**

Fermilab

Double Differential Cross Section

- Muon momentum and angle (less model dependence)



Phys.Rev. D88 (2013) no.3, 032001

Fermilab

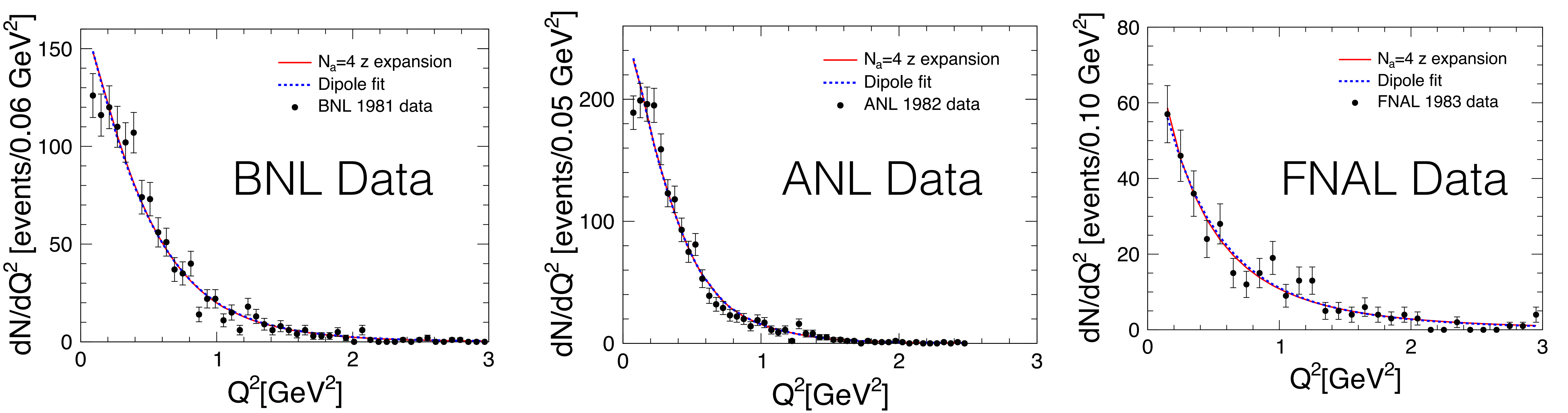
Axial Form Factor (z-expansion)

- 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

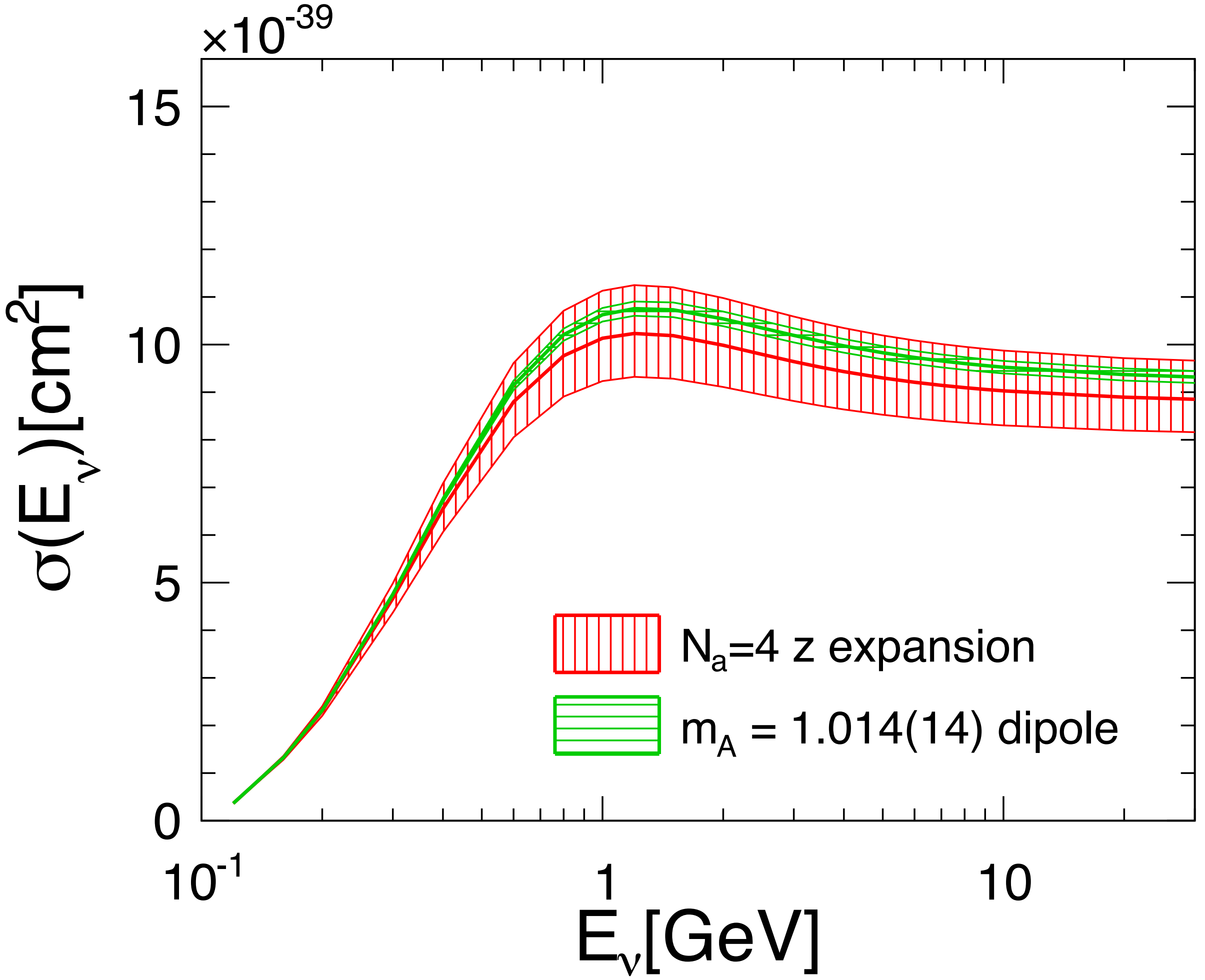
Deuterium data from BNL, ANL and FNAL



Aaron Meyer, MB, Richard Gran and Richard Hill, Phys. Rev D93(2

Axial Form Factor (z-expansion)

- The axial form factor is extracted from a joint fit to the all the available deuterium data



- Re-analyzing existing deuterium data
- For the dipole, the small error estimate results from the restrictive dipole ansatz and is likely an underestimate of the actual uncertainty
- z-expansion provides central values, accurate errors and correlations
-

Cross Section Measurements

Events Selected

Unfolding

Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

Bin-width

Acceptance

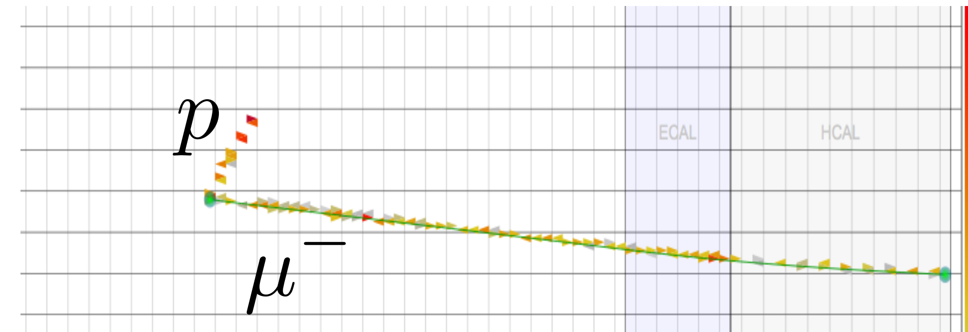
Flux

Targets

Fermilab

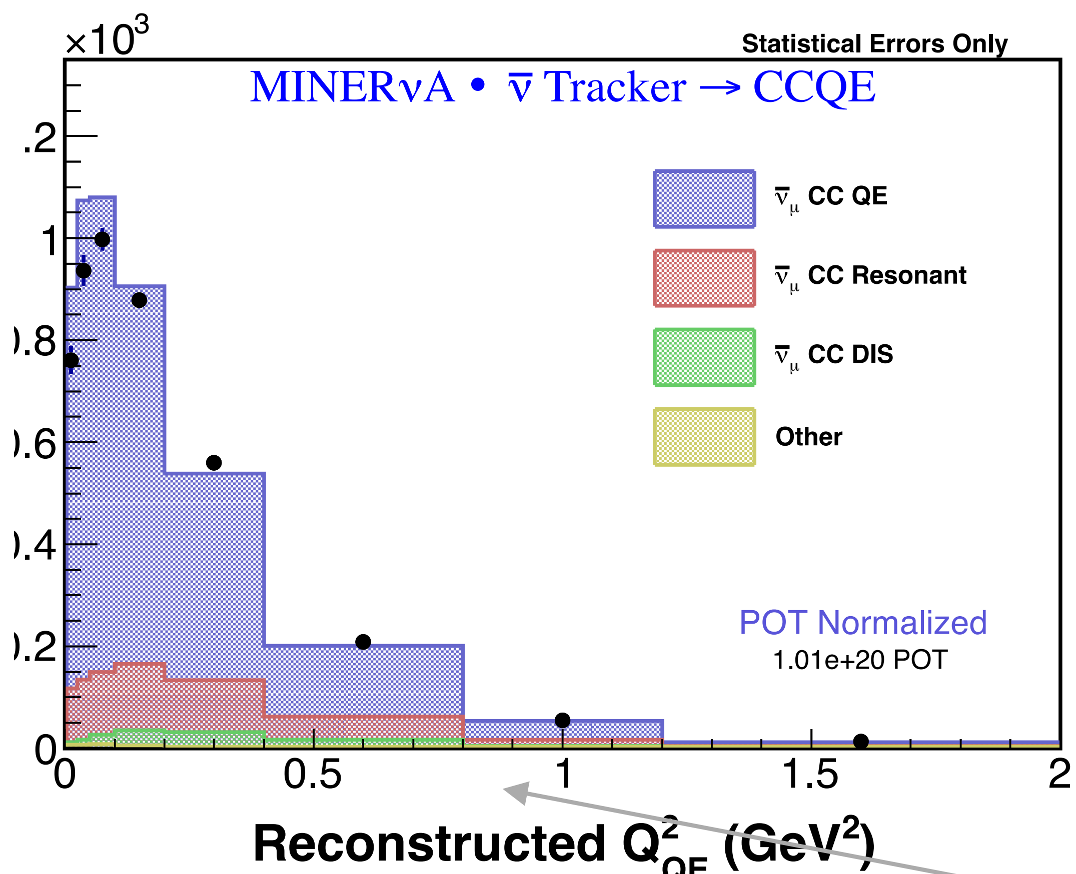
Signal and Background

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$



- We identifies the particles
- Measure properties of those particles
  - Momentum, angle and energy
  - Using the muon momentum and angle, we can compute the four momentum transfer $Q^2 = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta\mu)$ $\quad E_{QE} = \dfrac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$
  - Let's concentrate on describing how to measure the differential cross section as a function of Q^2

Selected events



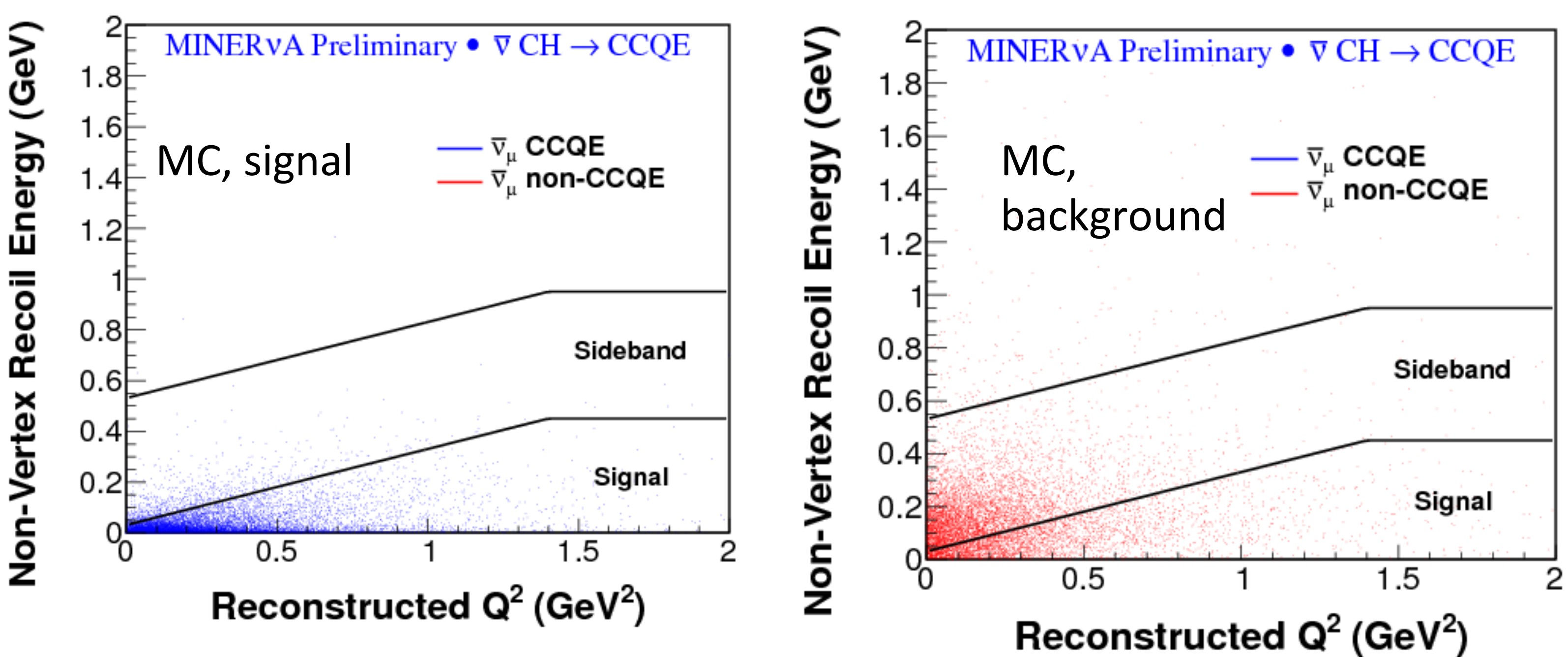
Main background from Resonant interactions

Fermilab

Background Prediction

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- We know the Monte Carlo models do not reproduce the real data
- Data is used to constrain the backgrounds
- Data driven background fit methods can reduce model-dependence
- An example from a MINERvA background constraint:
  - Taking the shape of the signal and background distributions in the Monte Carlo simulation
  - The relative weights of each of these distributions are varied until we get the combination that best matches the shape of the data
- Looking at the sideband region helps us to constrain the background in the signal region

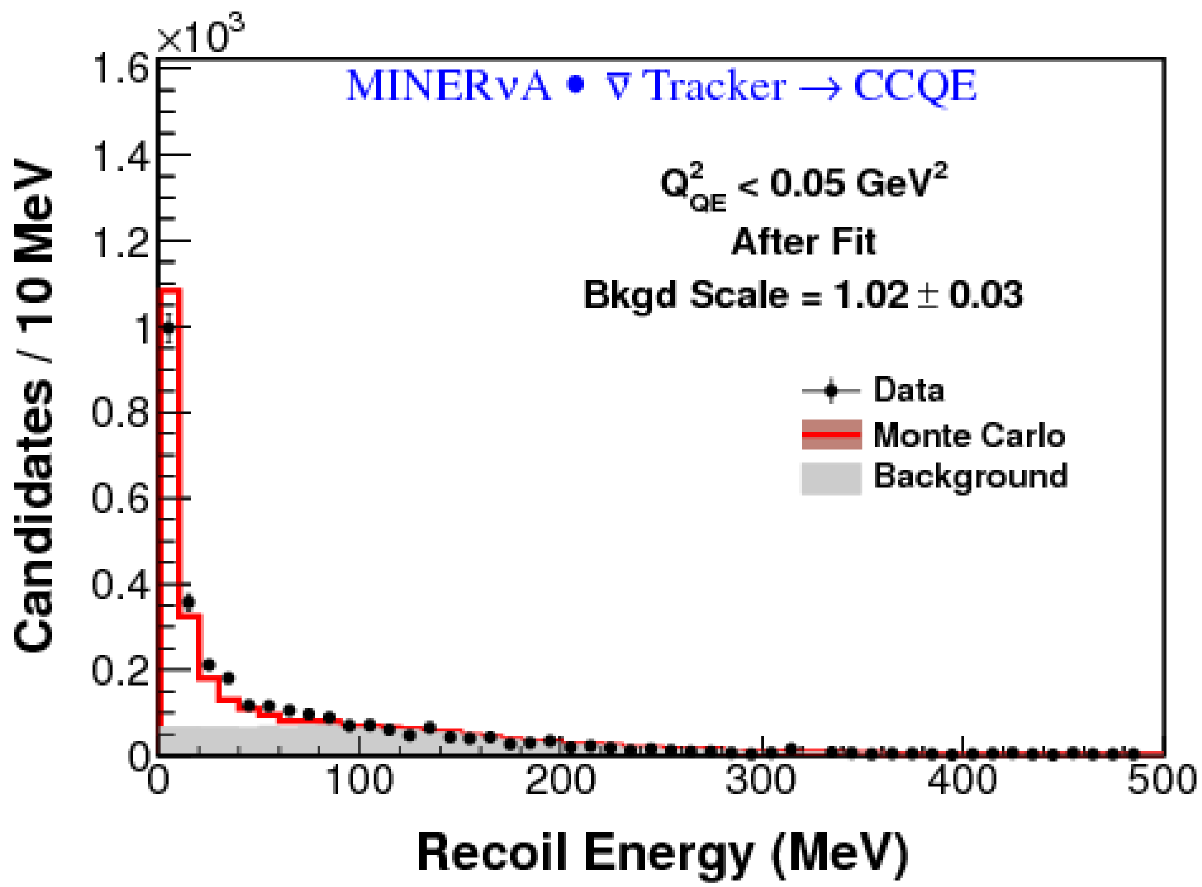


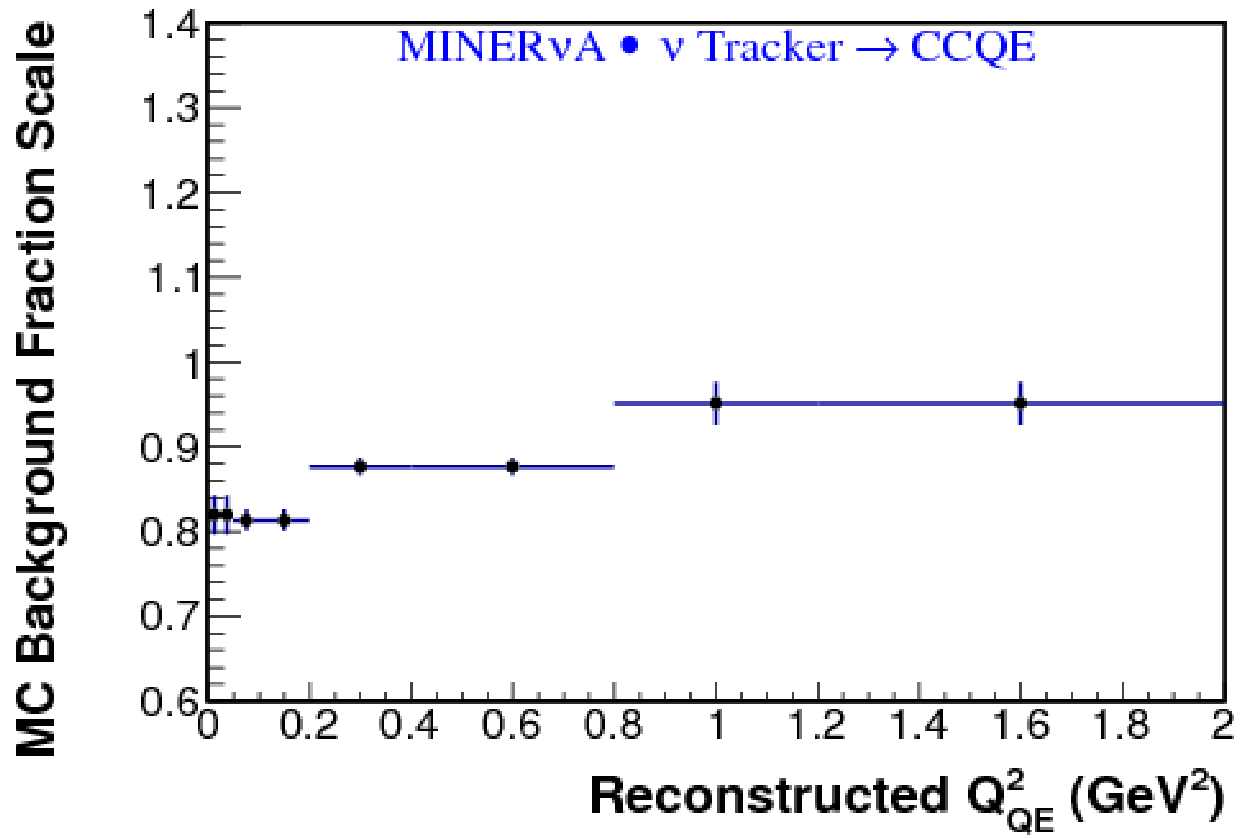
Fermilab

Example of Background Constraints

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- Background levels are estimated by fitting recoils distributions
- We obtain weights for each bin of Q^2





Fermilab

Background

- Background are very important part of the analysis
- This part of the analysis is where we spend most time in many analyzes
- To compute any cross section we need to remove the background
- Our simulation has some predictions for the background, can we just subtract the background?
- Remove the background as much as possible and we must constrain the remaining background

Events Selected

Unfolding

Backgrounds

$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_{\alpha}(\Phi T)(\Delta x)}$$

Bin-width

Acceptance

Flux

Targets

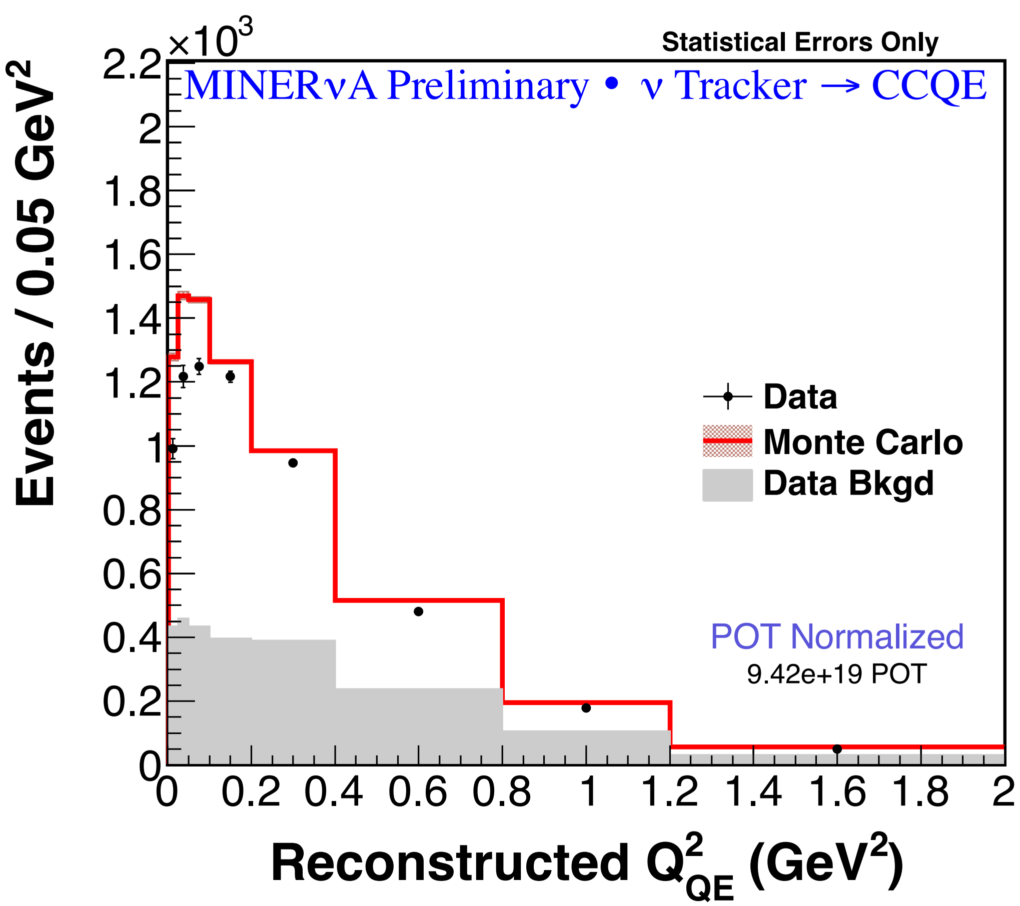
Fermilab

Background Subtraction

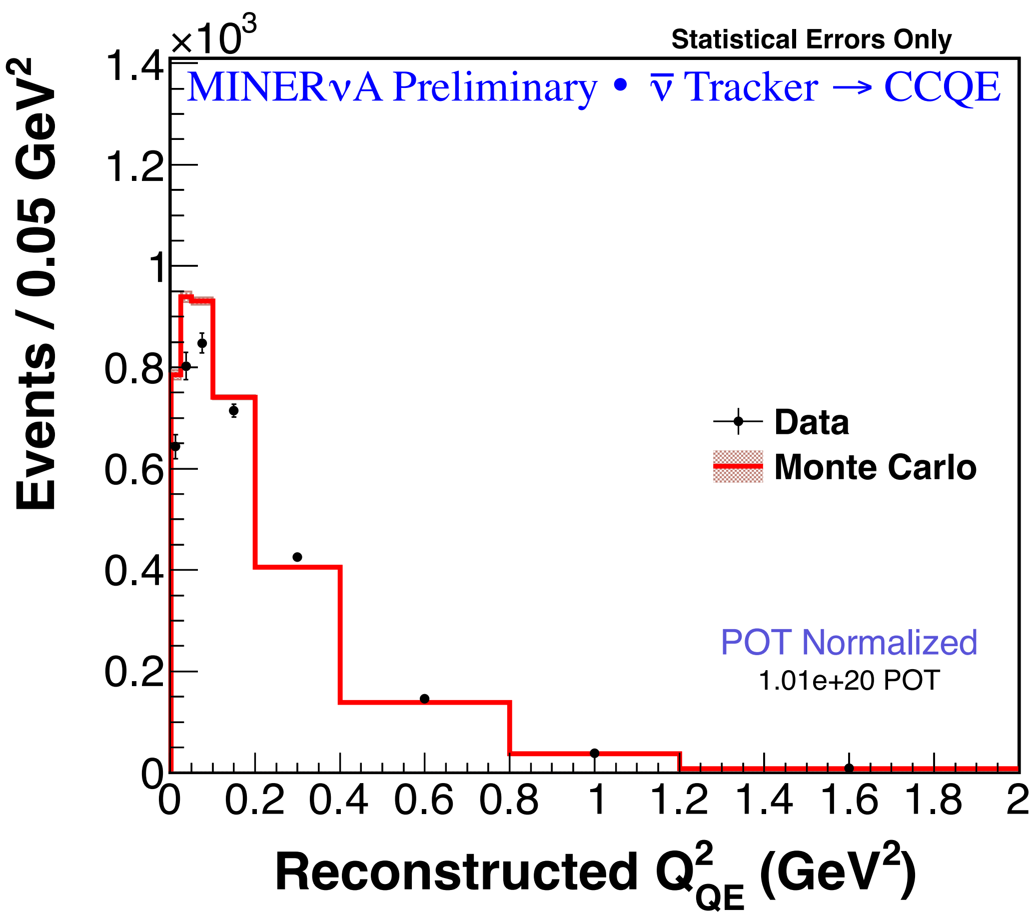
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- After the background is constrained with data, we subtract the predicted background contribution from each bin of the desire quantity we want to measure

Selected sample with background



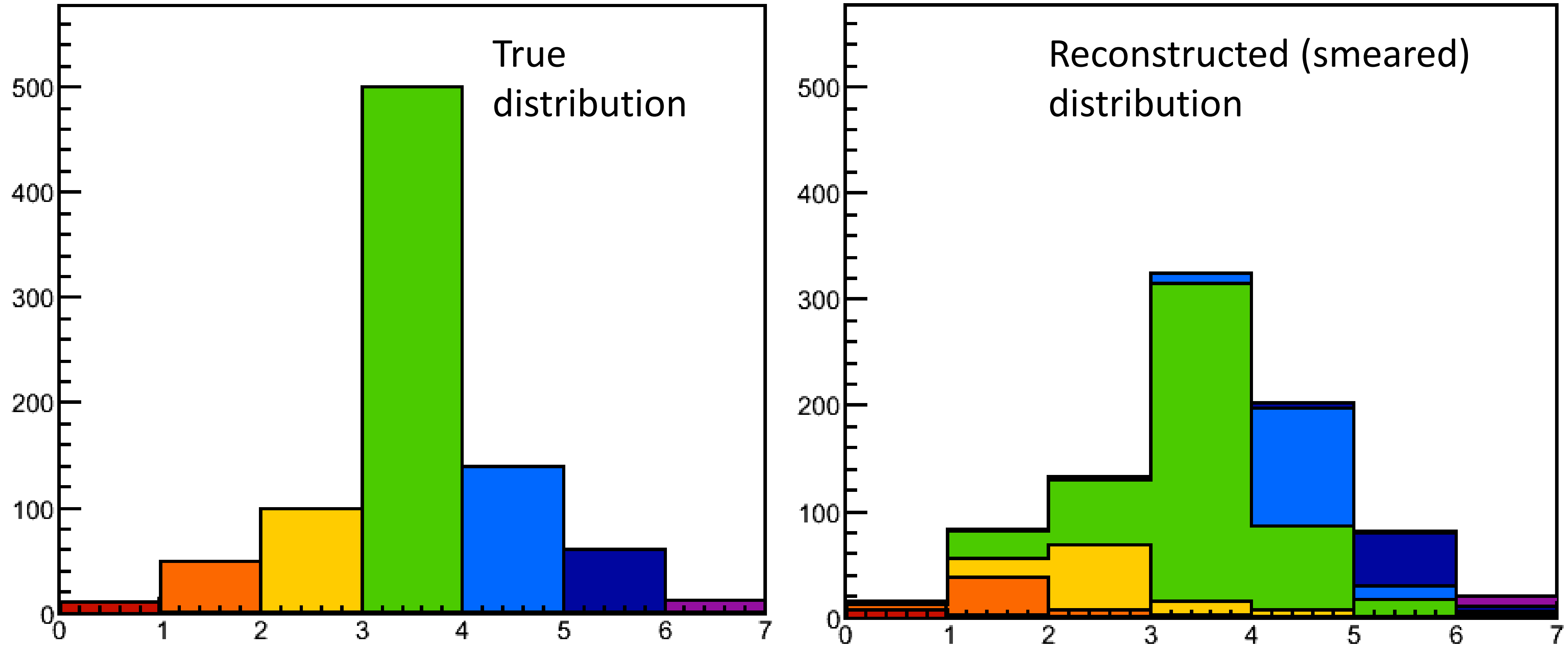
After background subtraction



Unfolding

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

- We can't measure (or reconstruct) events with perfect precision, so we will always reconstruct some events into the wrong bin



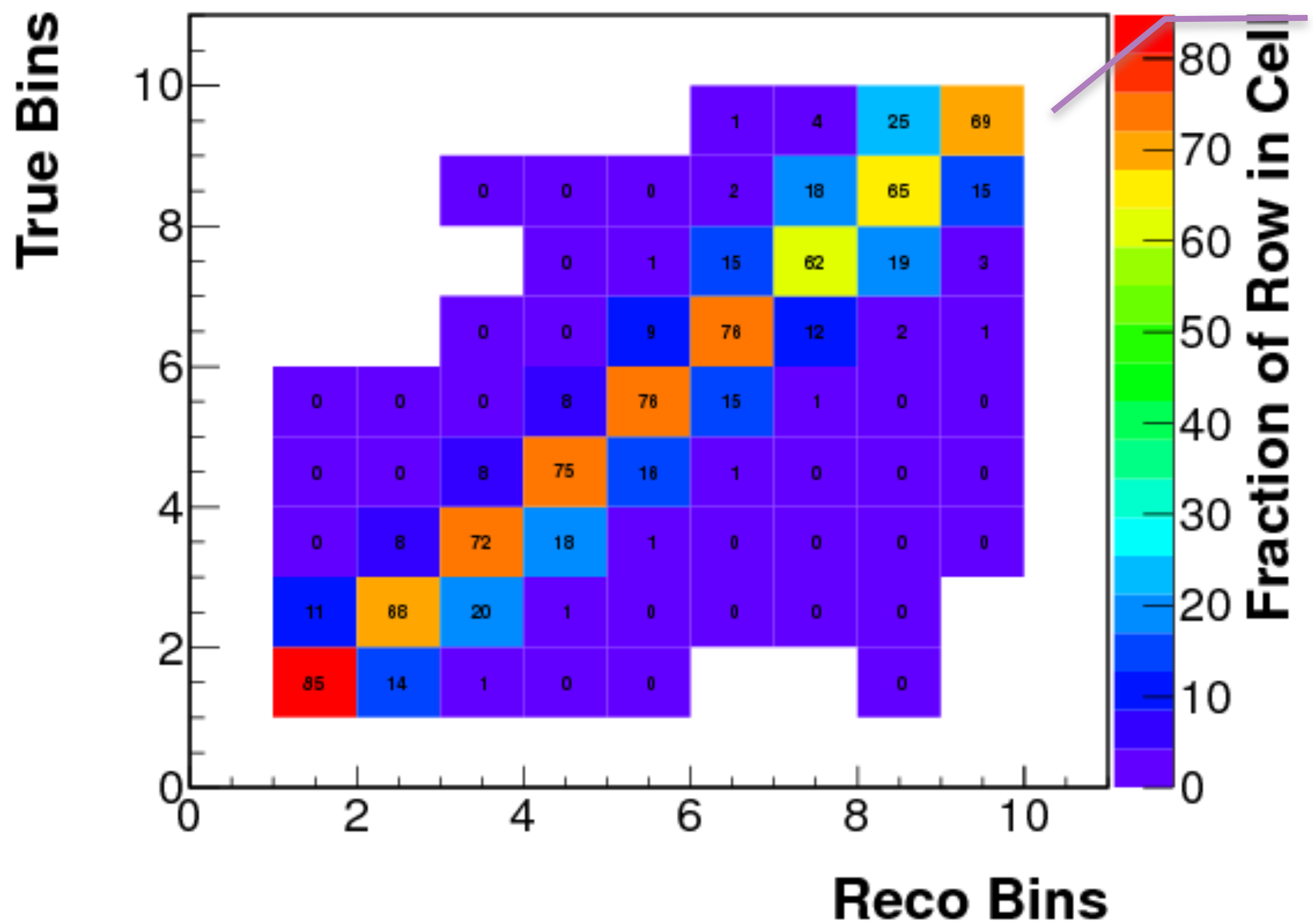
- This has the effect of smearing out the features of our true distribution
- Correcting for the effects of detector smearing, which causes some events to be reconstructed into the wrong bin. The goal is, when presented with a smeared distribution, to recover out true distribution

Cheryl Patrick, MINERvA 101

Unfolding

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

- Example from Quasi-Elastic scattering



Diagonal corresponds to events reconstructed in the right bin

- To get the unsmearing matrix U, we must invert the migration matrix

Cheryl Patrick, MINERvA 101

Fermilab

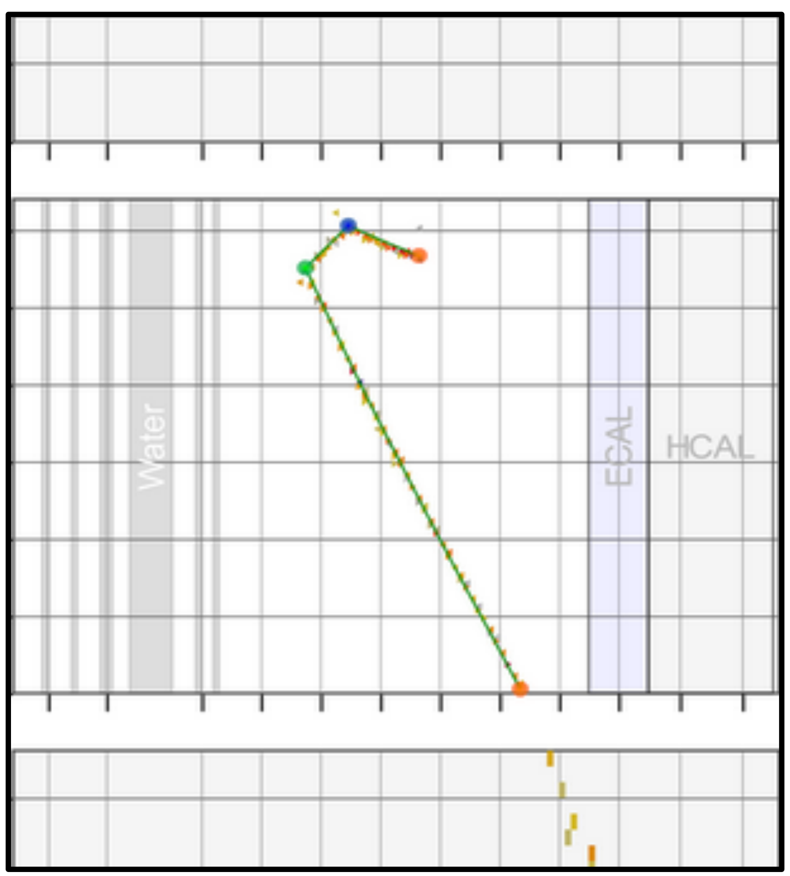
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

Efficiency Correction

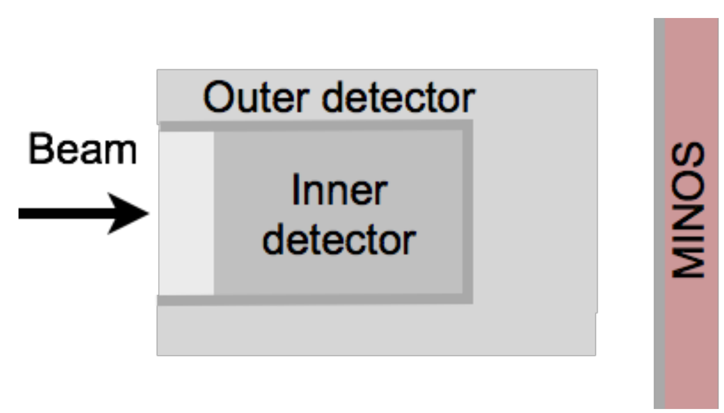
- A measure of how often we select signal events
- Inefficiency comes from reconstruction and detector geometry

$$\varepsilon = \frac{\text{number of signal events after event selection}}{\text{number of signal events in Monte Carlo}}$$

- An example from detector acceptance



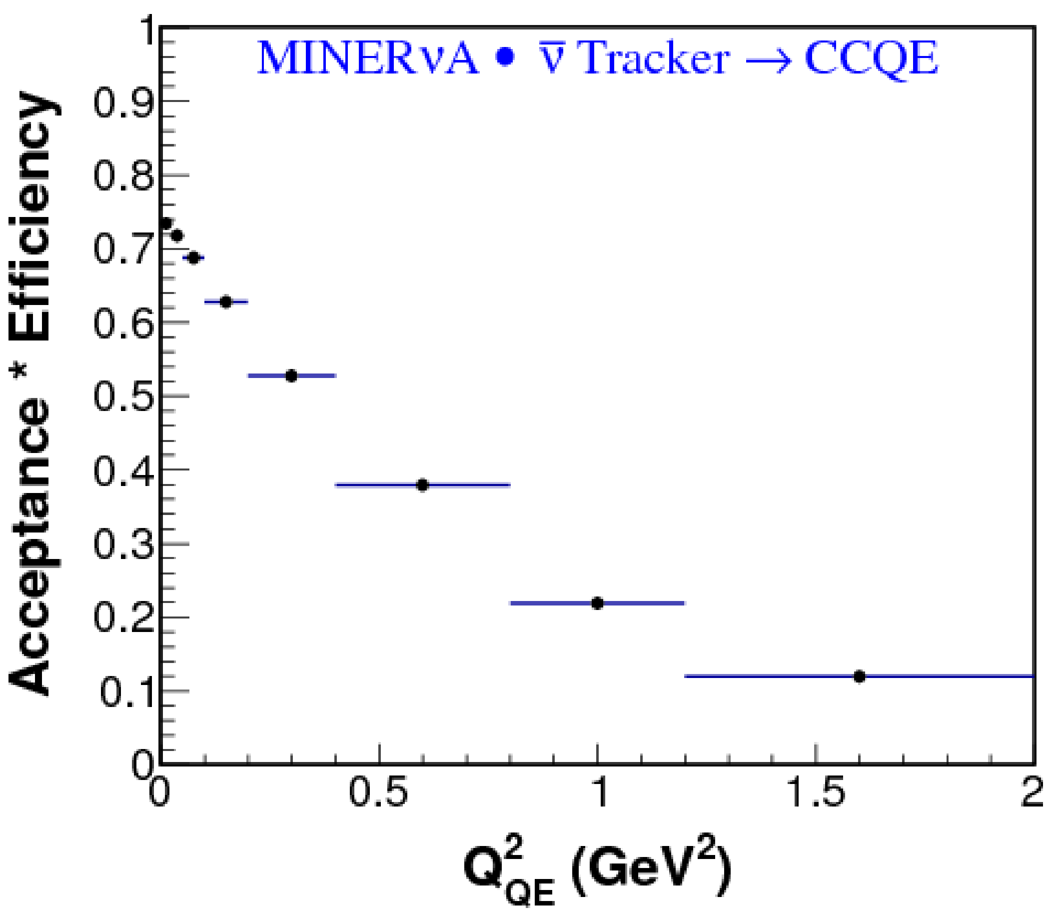
Some analyses require muon track to be matched to a track in MINOS. Events where the muon exits the side of detector will be rejected

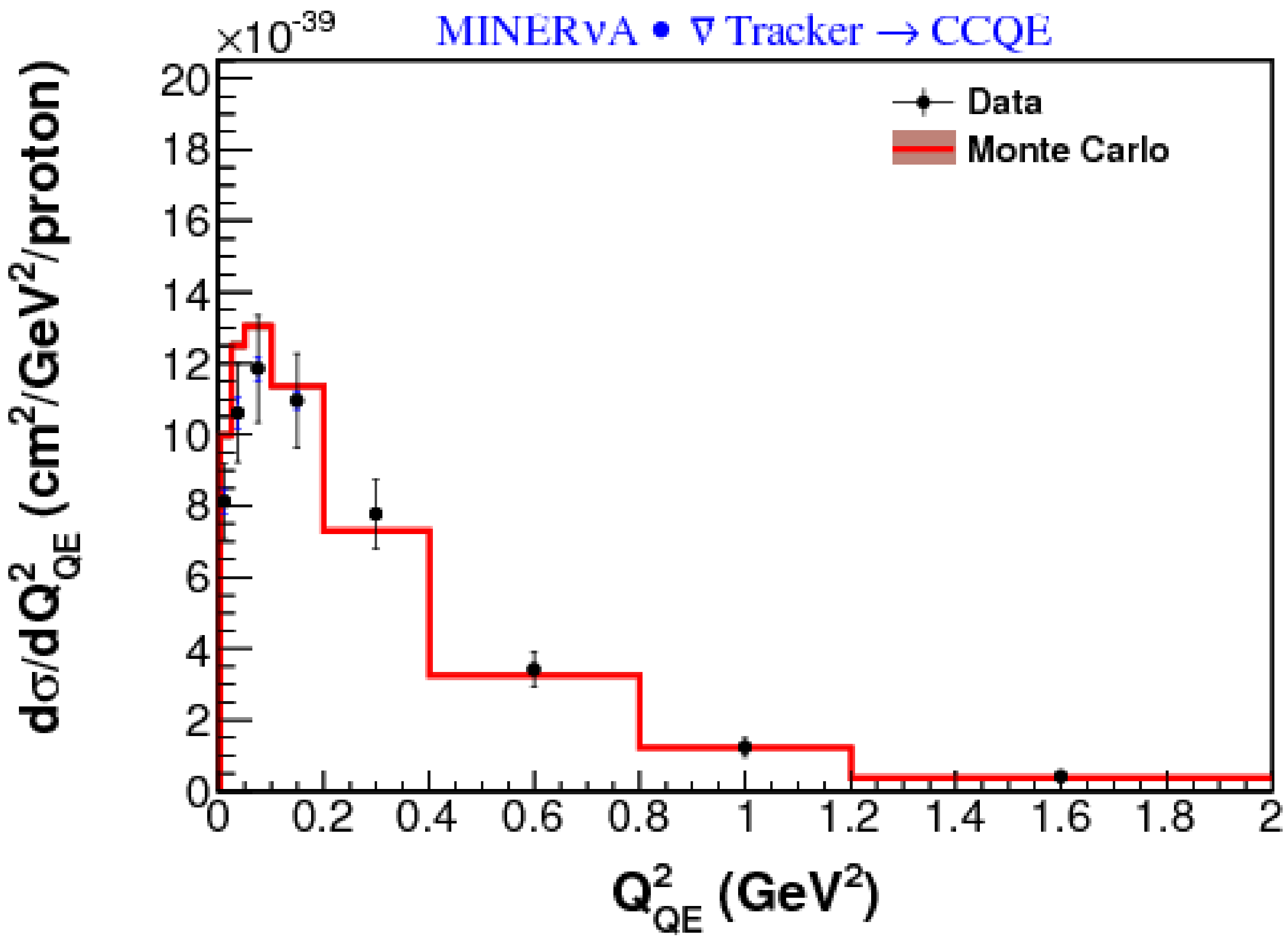


Efficiency Correction

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha (\Phi T)(\Delta x)}$$

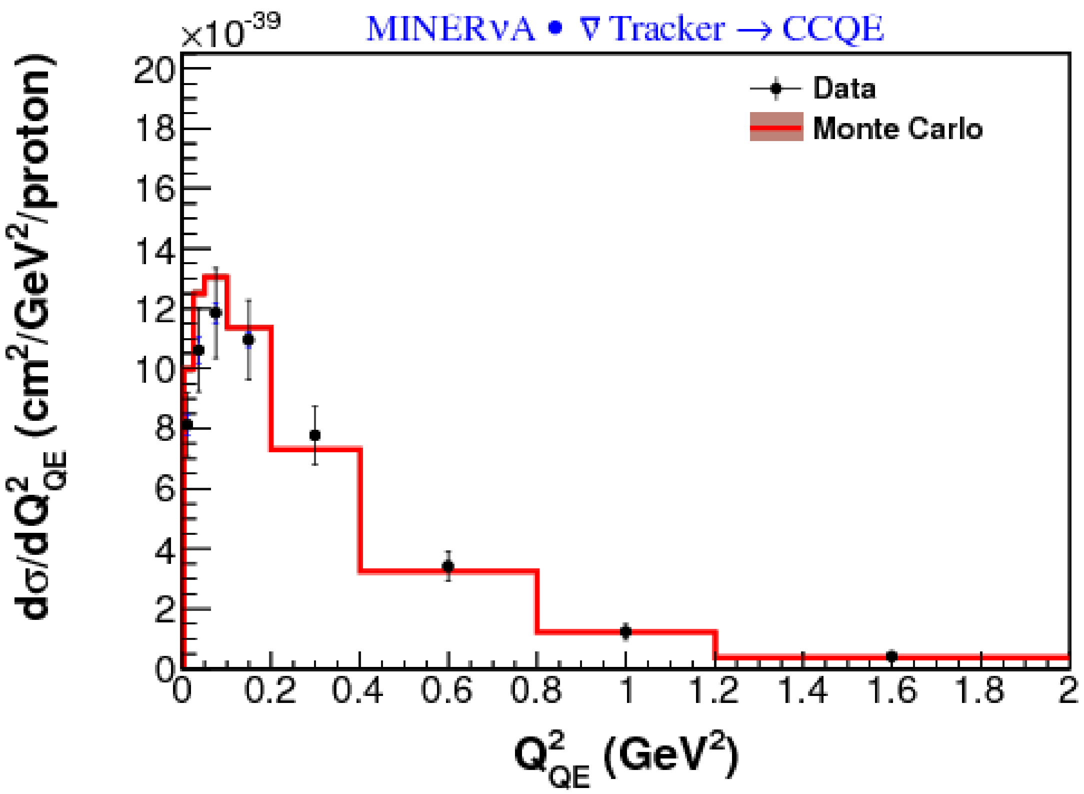
- Unfolded distributions are normalized by efficiency, flux and proton number to produce final cross section

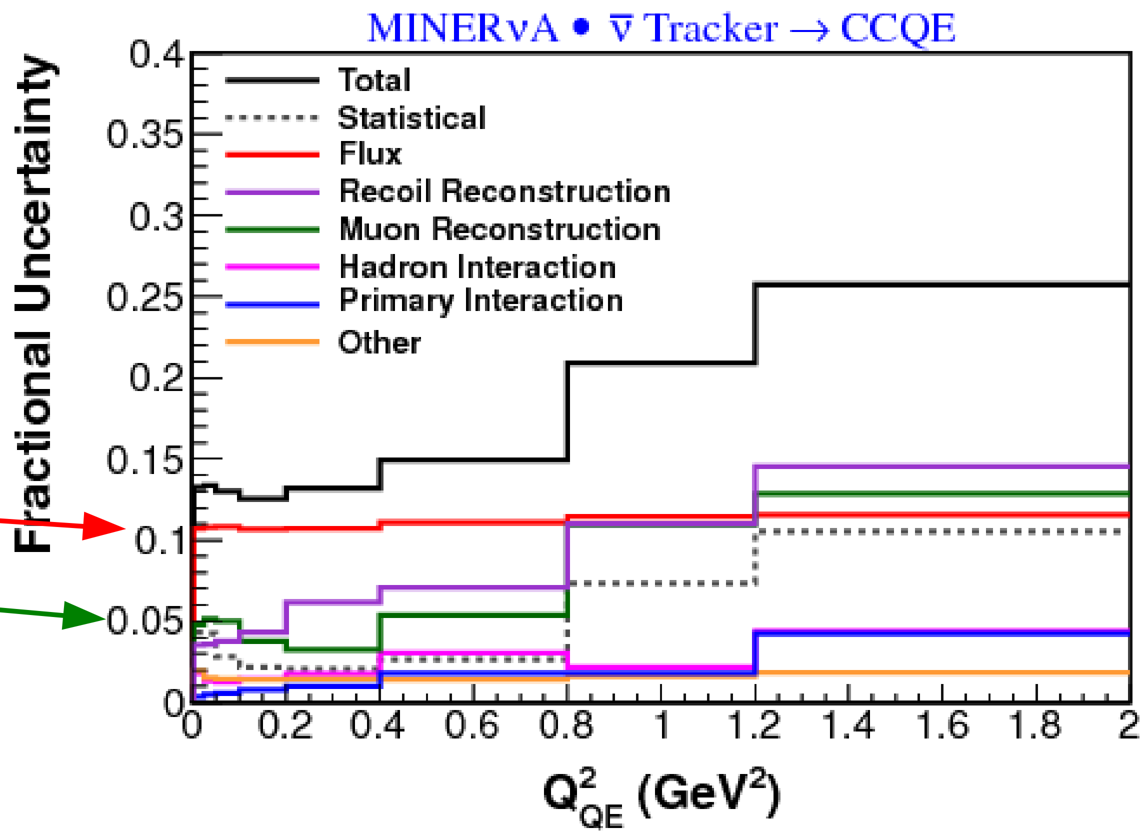




Fermilab

Systematic Uncertainties



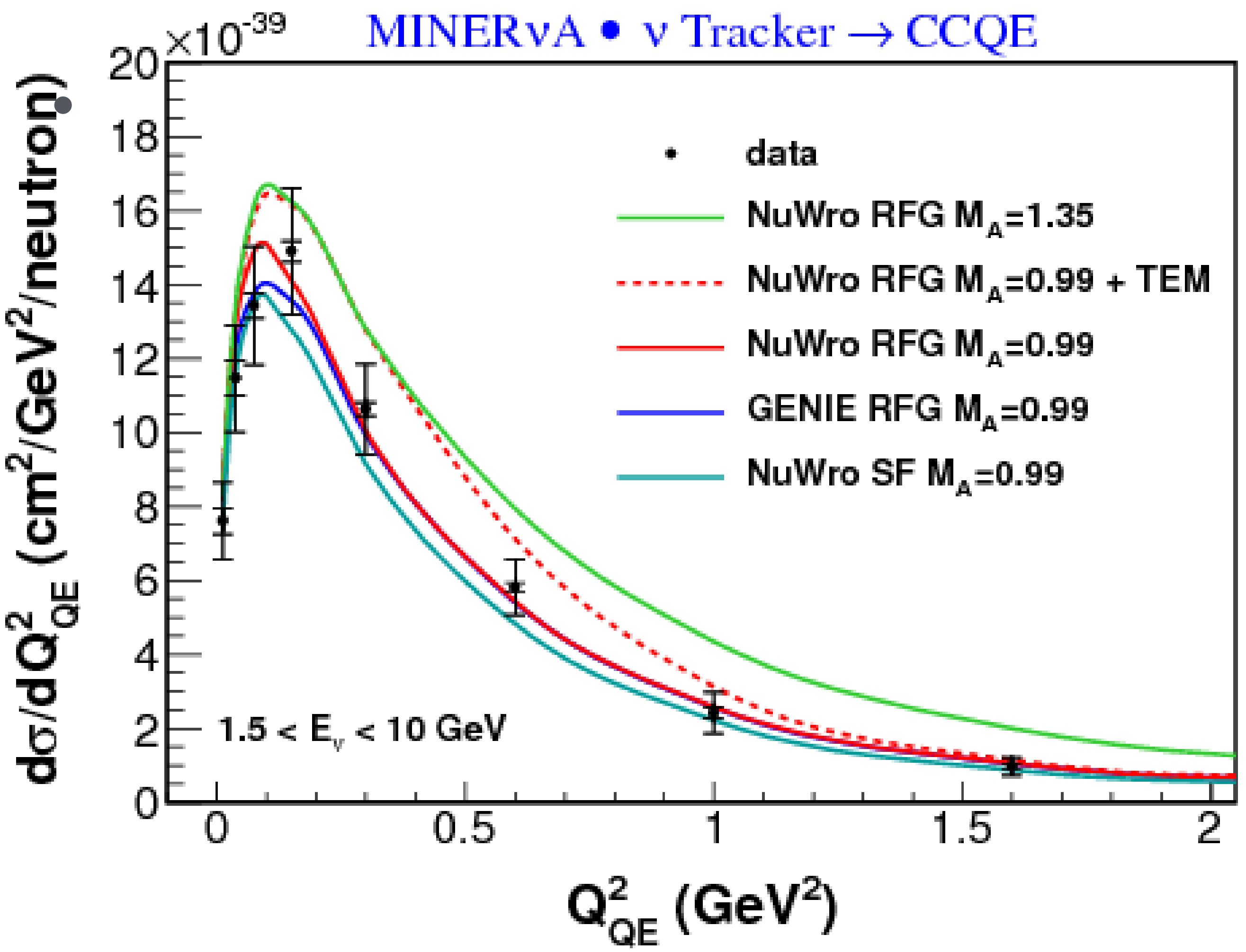


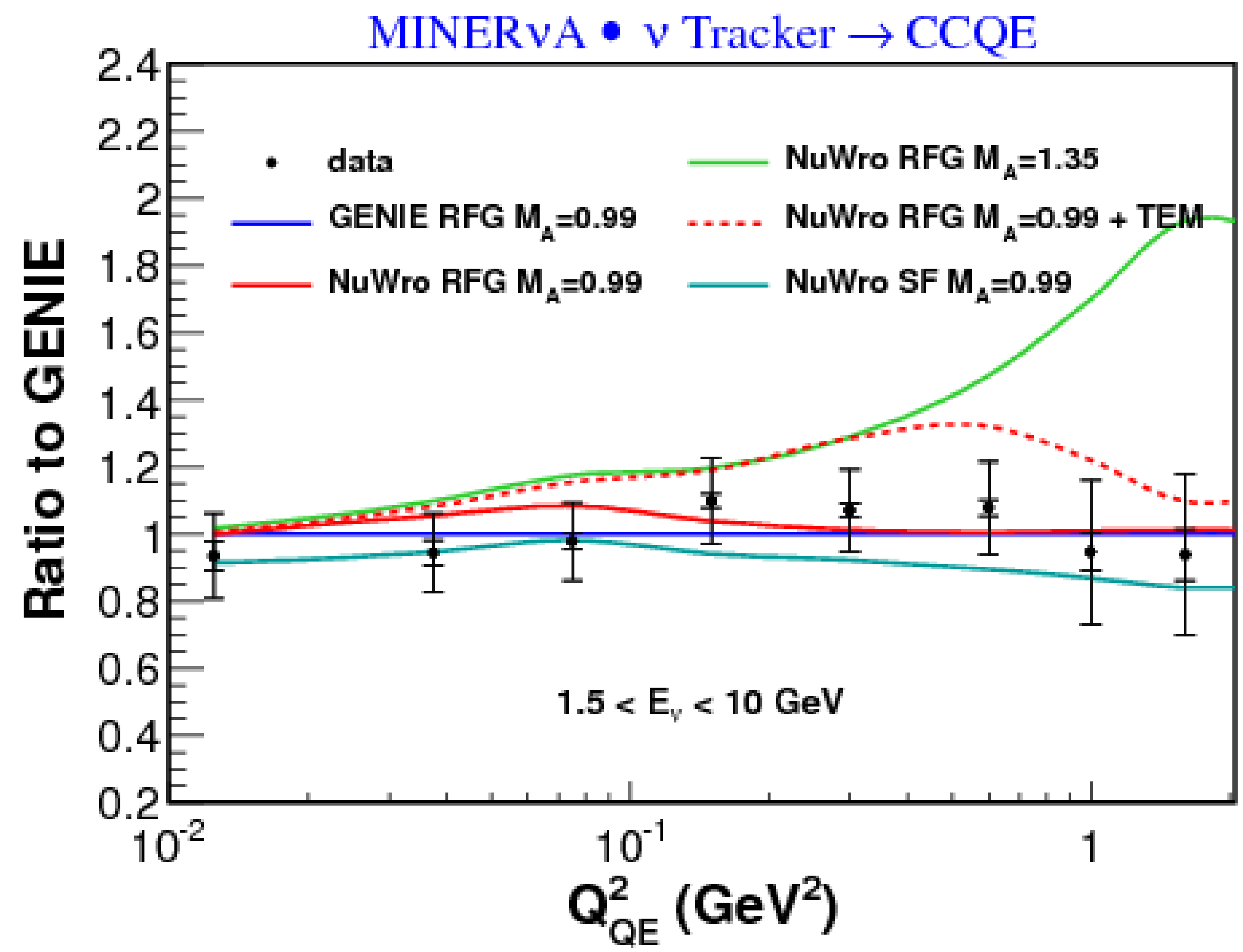
Flux uncertainties

Muon Reconstruction Uncertainty

Comparing with Models

- Data do not agree with some models

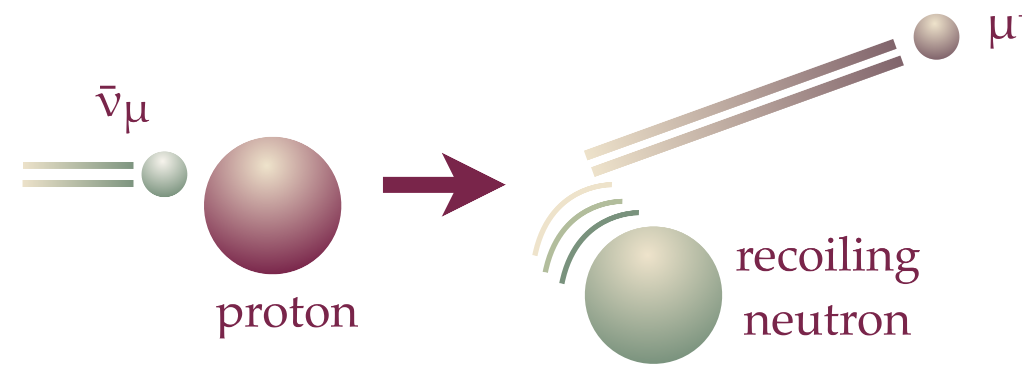




Phys. Rev. Lett. 111, 022501 (2013)

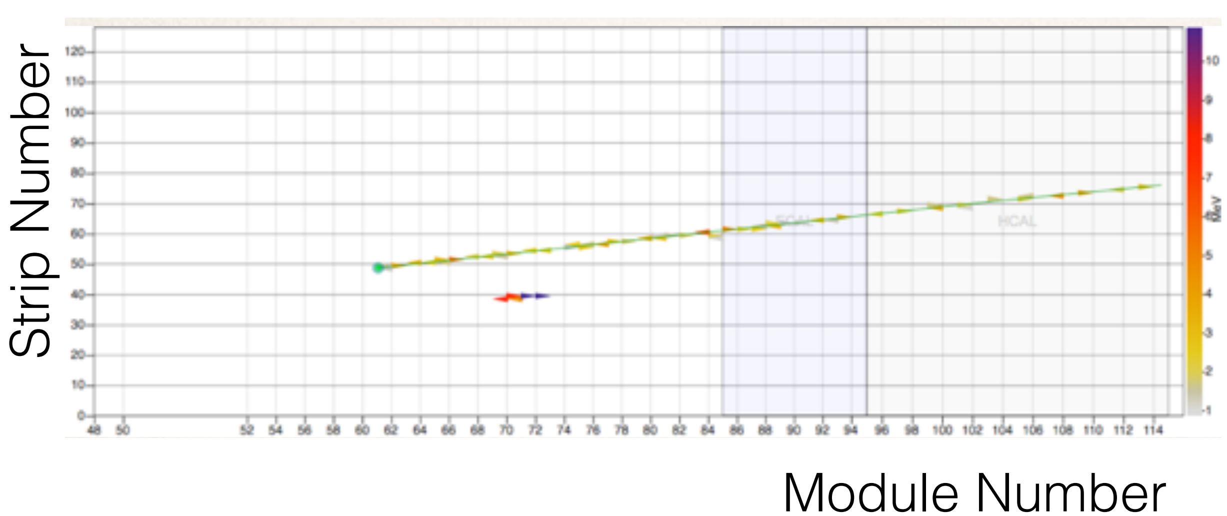
Double Differential Cross Sections (Antineutrinos)

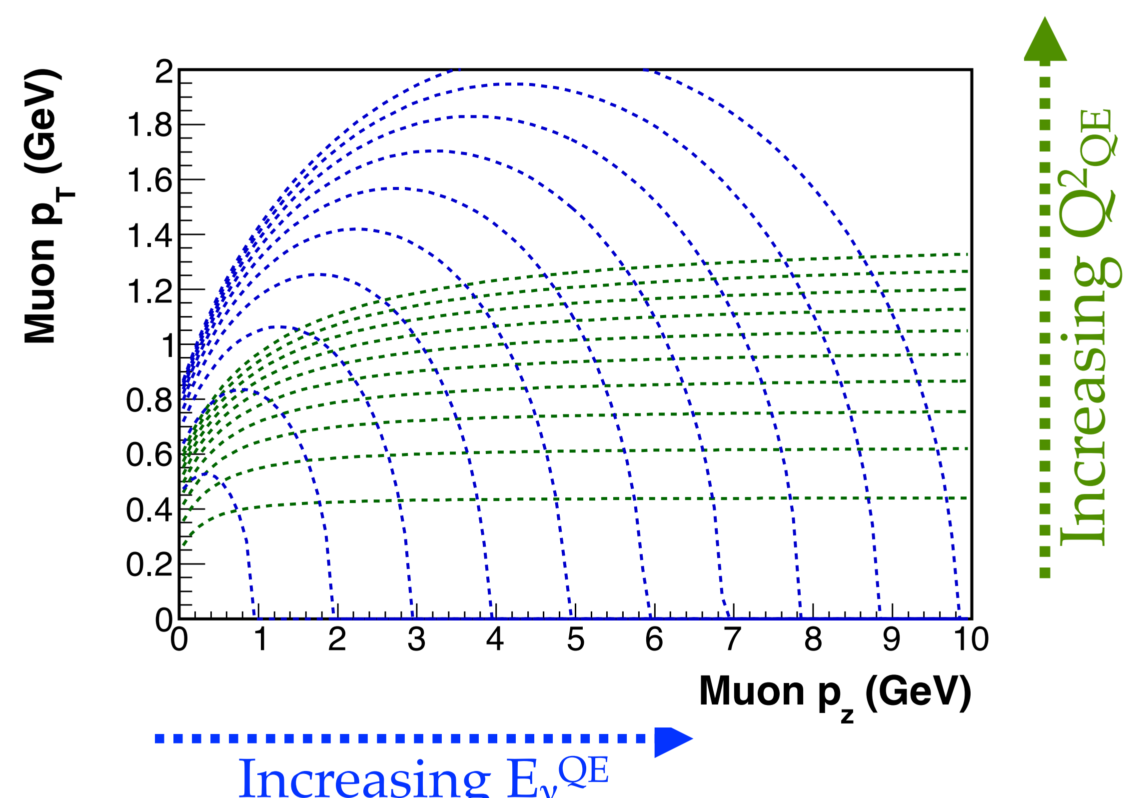
- Using the kinematic of the muon
- Double differential cross sections for antineutrinos



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

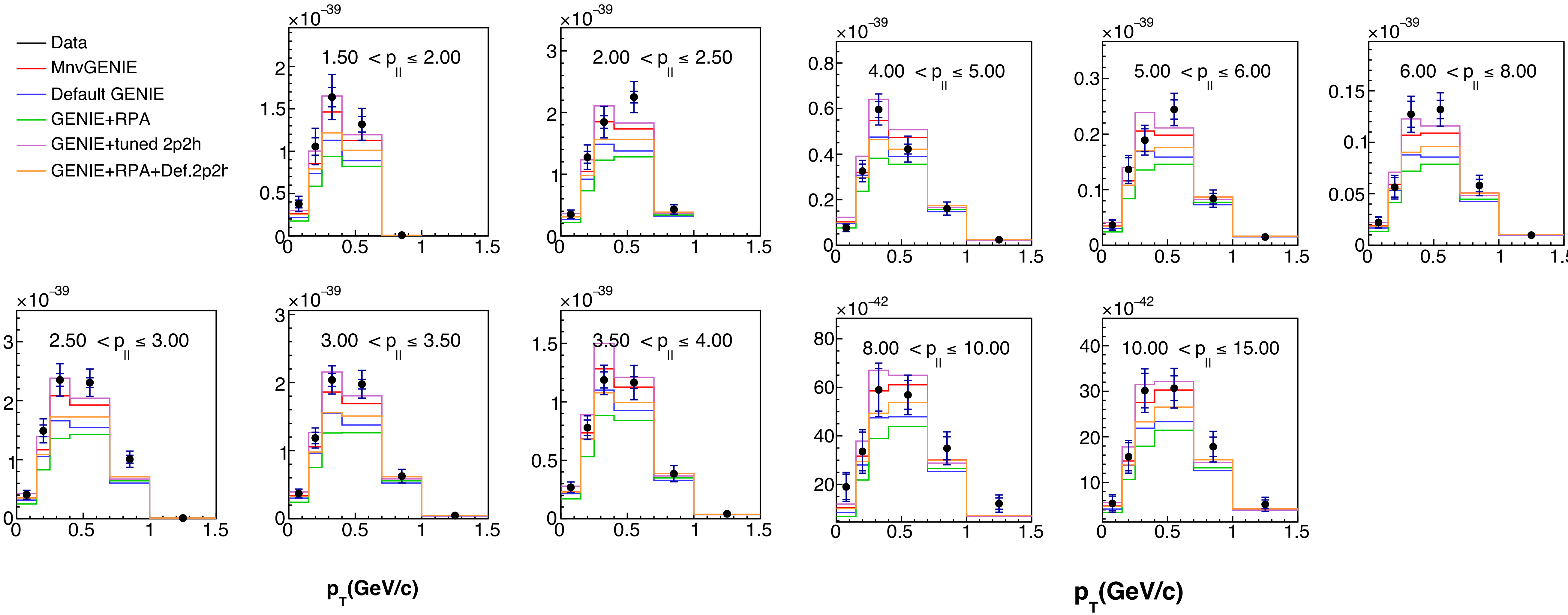
- Muon longitudinal P_{Z_μ} and transverse momentum P_{T_μ} are measurable quantities
- P_{Z_μ} and P_{T_μ} are less model dependent than Q^2





Fermilab

Double Differential Cross Sections for Antineutrinos

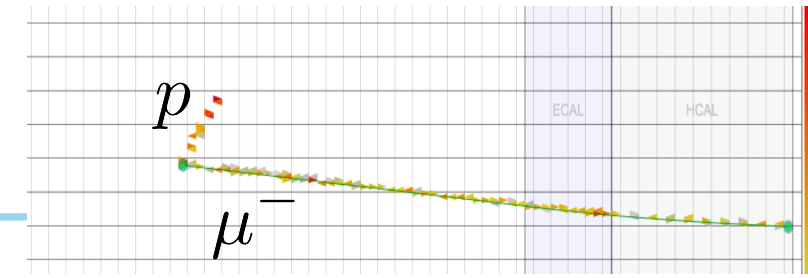


Phys.Rev. D 97 116 (2018) no. 5, 052002

- We see agreement between data and a simulation that includes nuclear effects

Fermilab

Initial Neutron Momentum

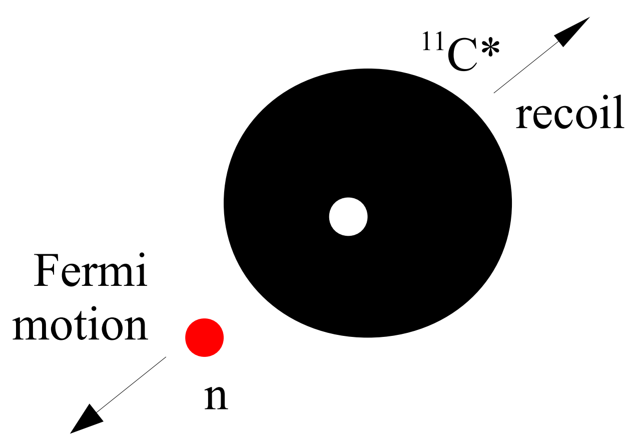


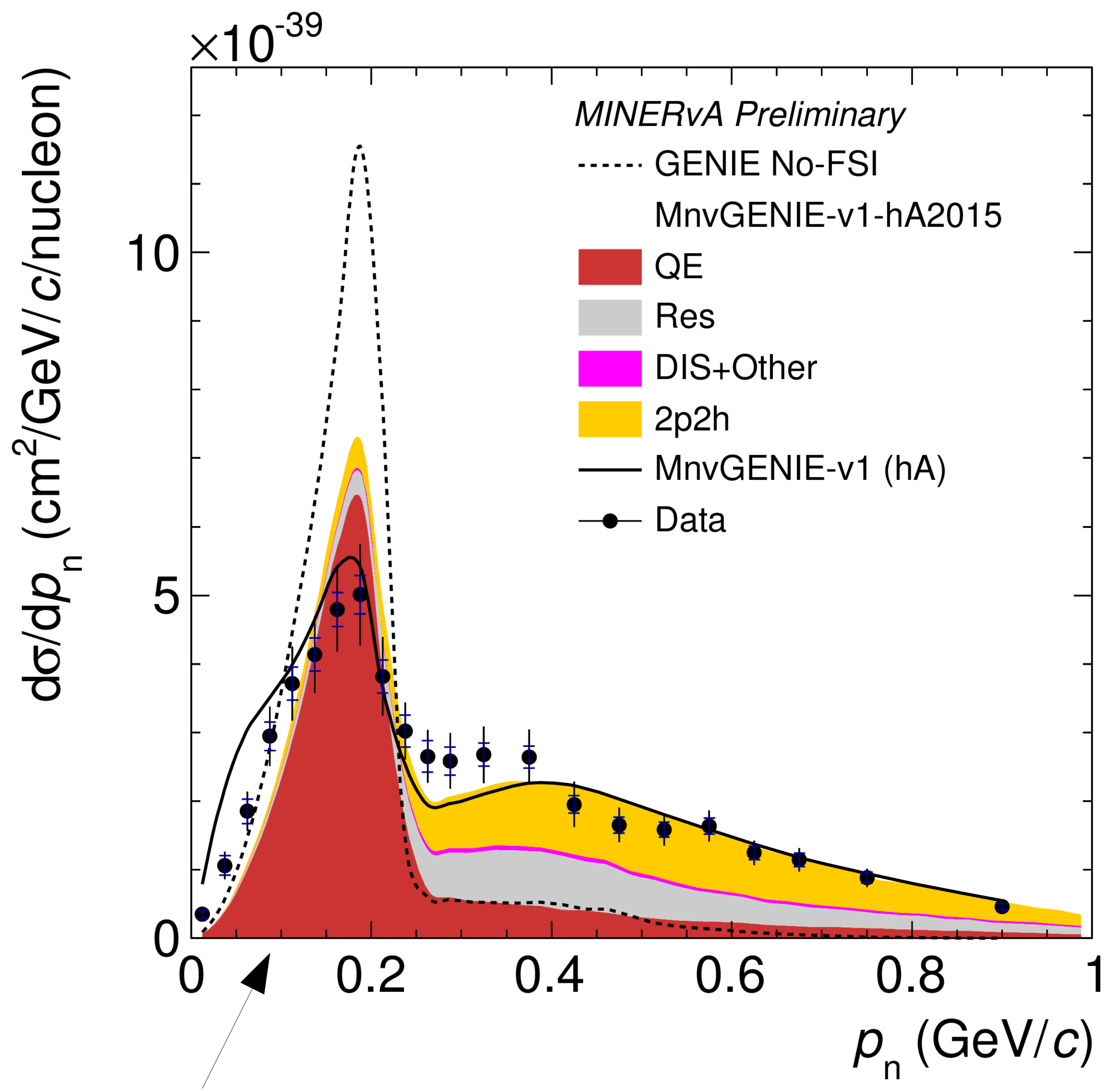
- Differential cross section in initial struck neutron momentum p_n

Transverse: $0 = \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'} - \delta\vec{p}_T$

Longitudinal: $E_\nu = p_L^{\ell'} + p_L^{N'} - \delta p_L$

New variable: $p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$

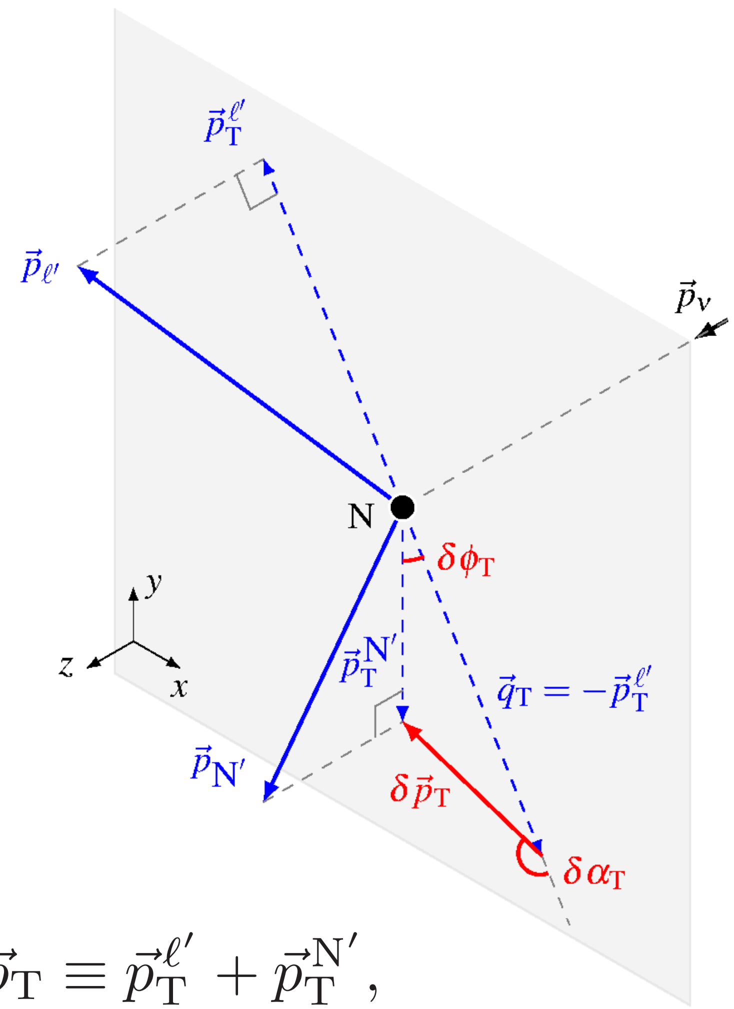




Fermilab

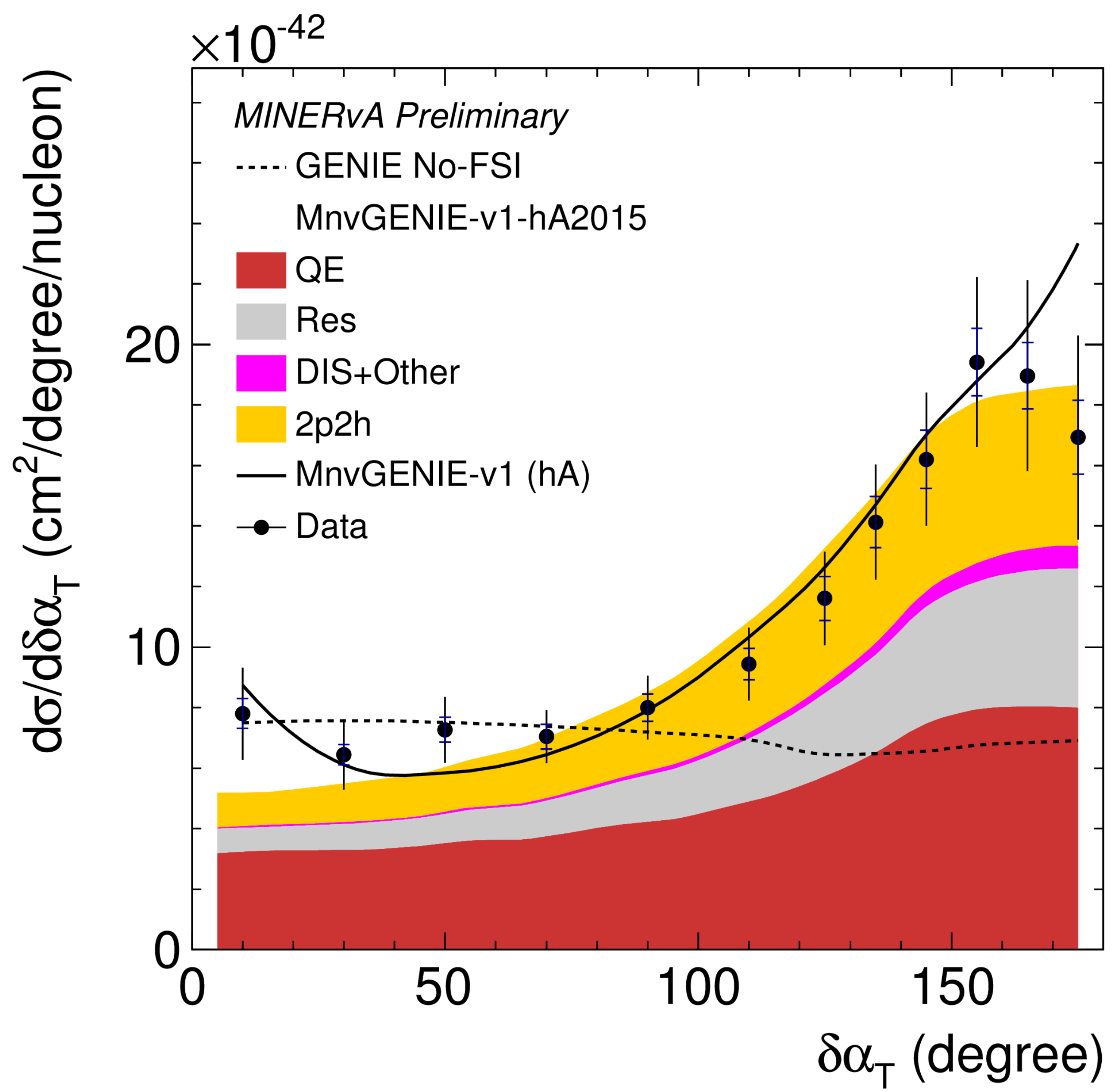
Transverse Kinematic Imbalances

- Differential cross section in transverse boosting angle $\delta\alpha_T$
  - The transverse boosting angle $\delta\alpha_T$ represents the direction of the transverse momentum imbalance



$$\delta\vec{p}_T \equiv \vec{p}_T^{\ell'} + \vec{p}_T^{N'},$$

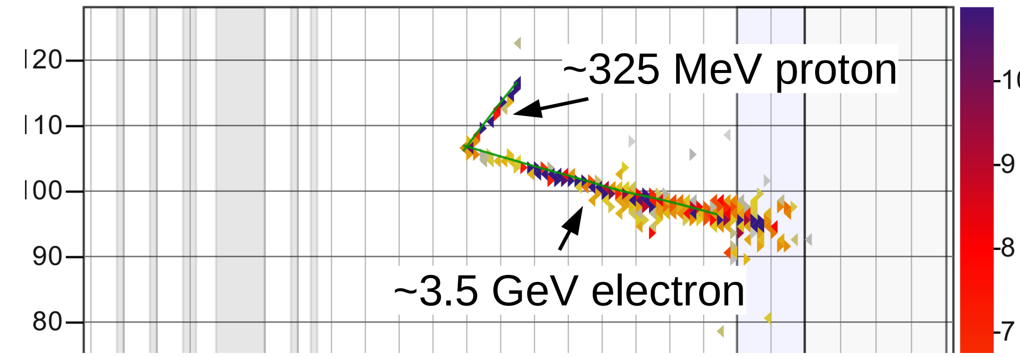
$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\delta p_T},$$

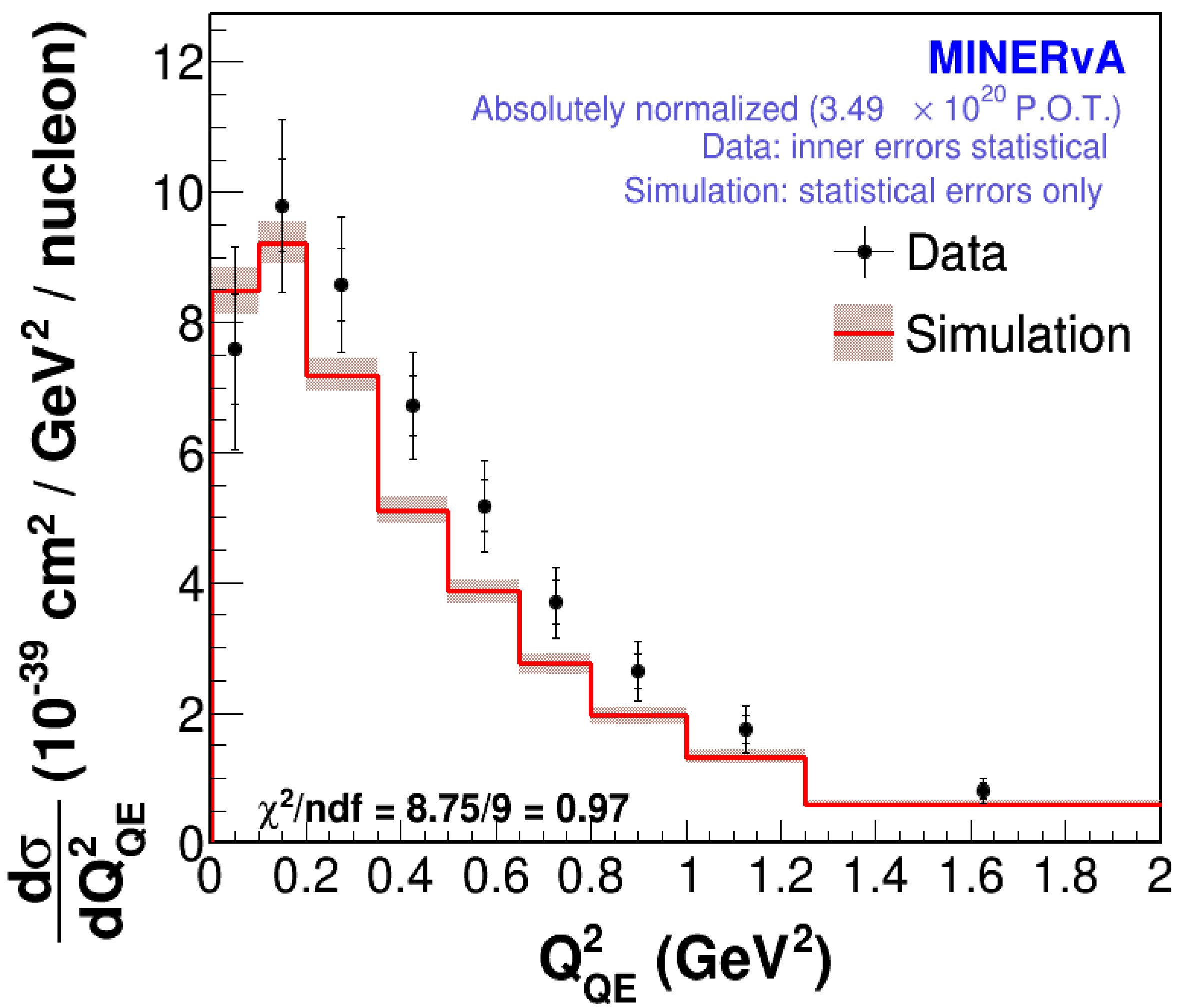


Fermilab

ve CCQE Measurements

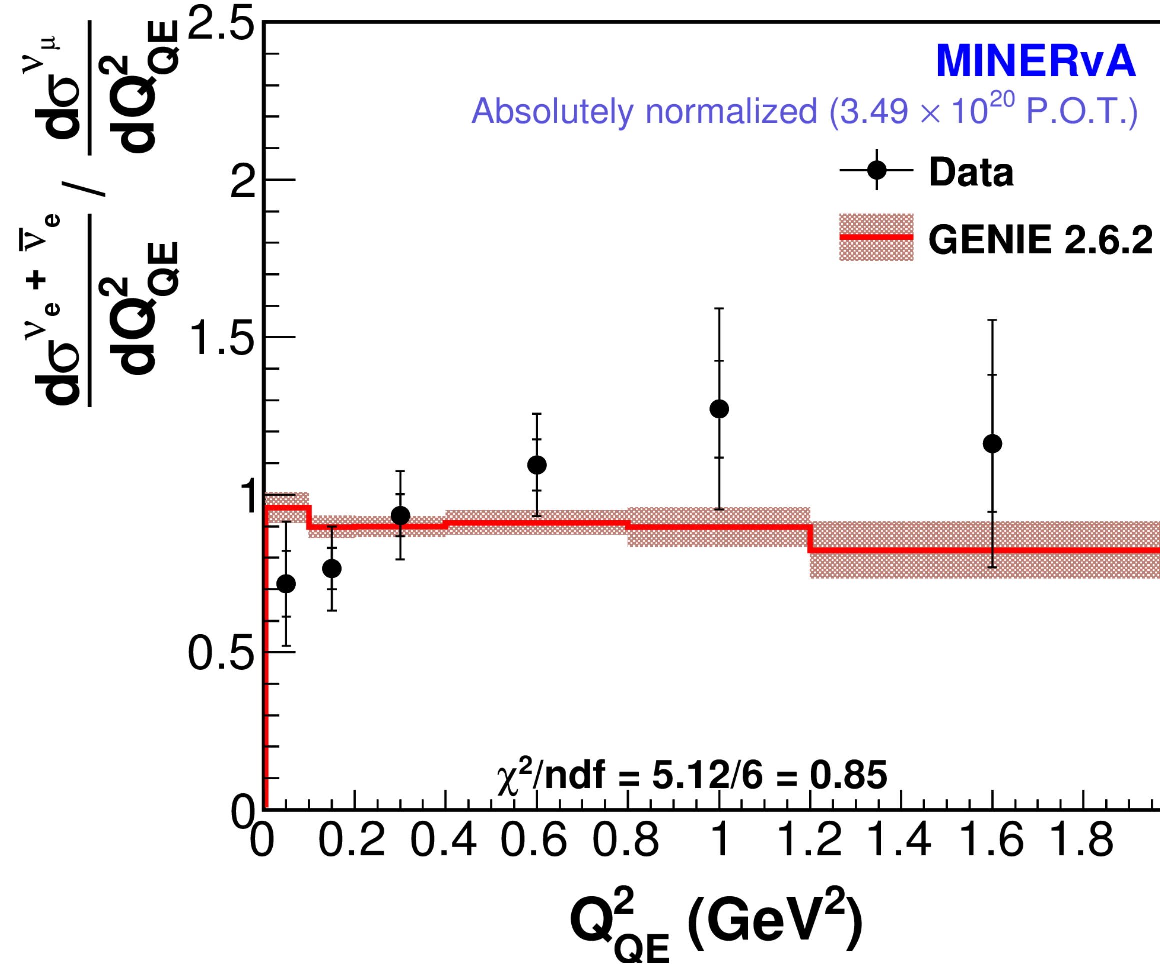
- CCQE-like definition: any number of nucleons, but no other hadrons allowed in final state





Phys. Rev. Lett 116 (2016) 081802

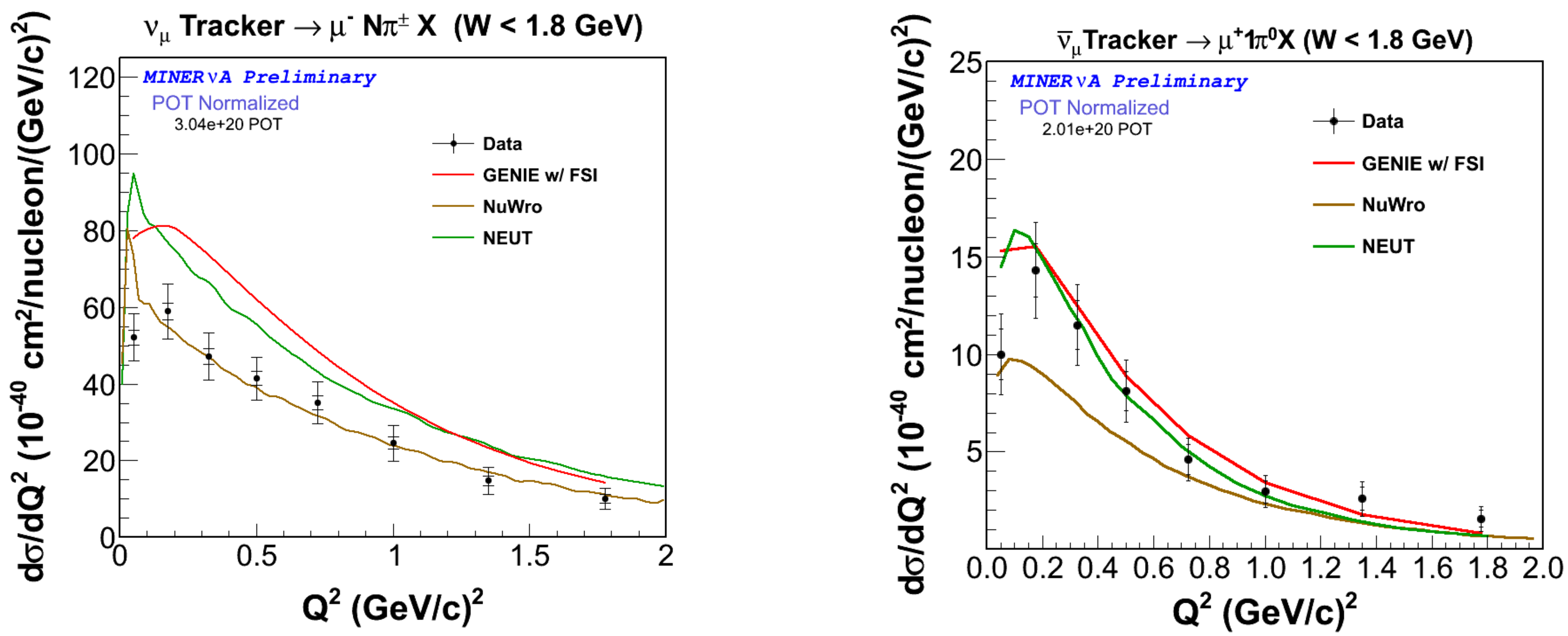
ν_e to ν_μ differential cross section ratio



Ratio is consistent with 1.0

Multi pi zone (W<1.8 GeV)

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

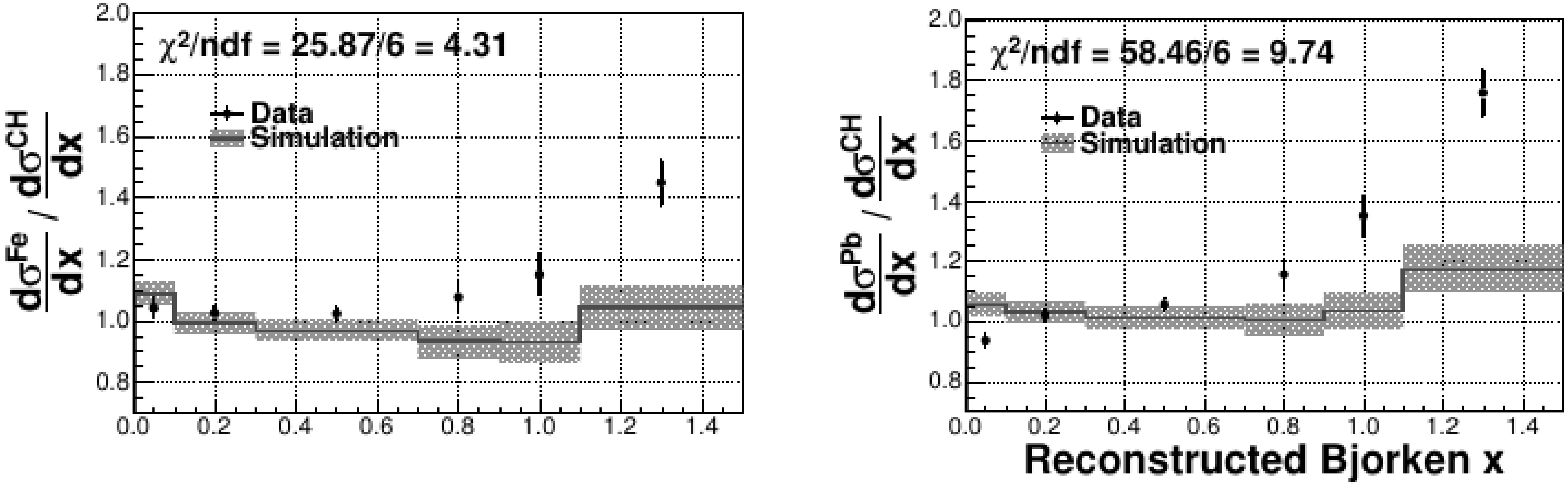


- In charged pion both GENIE and NEUT over estimate the cross section
- In neutral pions GENIE and NEUT agree better with data than NuWro, expect in the first bin
- The Q^2 spectrum provides the most detail and no single model describes both the pion and pious distributions
- Experimental data pointing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

Ratio between nuclear targets (CC Inclusive) from MINERvA

- MINERvA is starting to study X dependent nuclear effects with neutrinos
- Measurements of CC inclusive ratios for iron to scintillator and lead to scintillator

Minerva, Phys.Rev.Lett. 112 (2014) 23, 231801



- 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 dominants for the oscillation experiments
- We need better understanding the A dependence of inclusive scattering

Fermilab

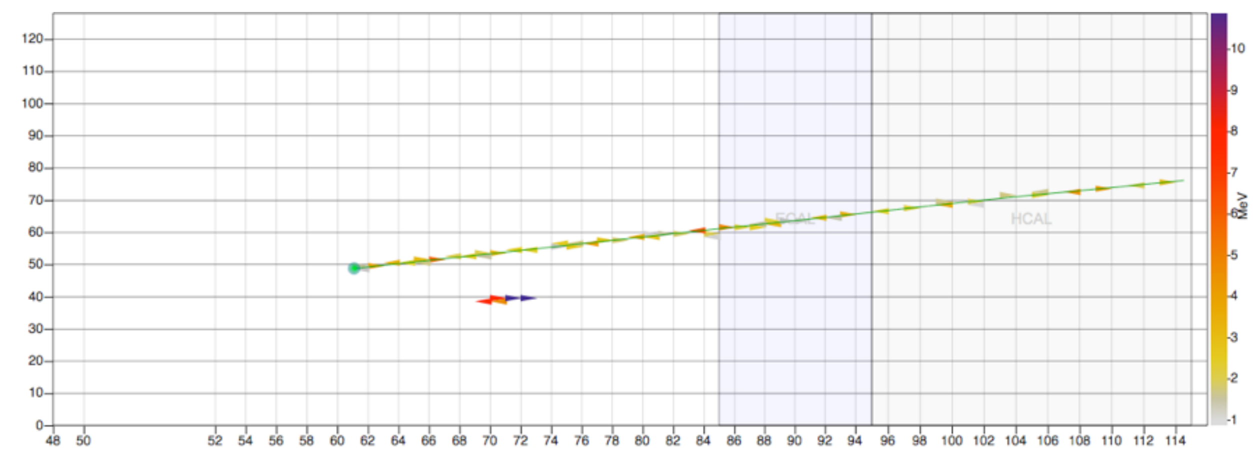
Summary

- Neutrinos are great probes to answer fundamental questions about the nature of matter and the evolution of the universe
- Several discoveries since the first experimental evidence of neutrinos
- Several challenges from the theoretical model side and experimental side to understand neutrino interactions
- 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
- Fermilab has a rich neutrino program looking to answer some of the questions in neutrino oscillations

Back Slides

CC0pi Antineutrino Event Selection and Signal Definition

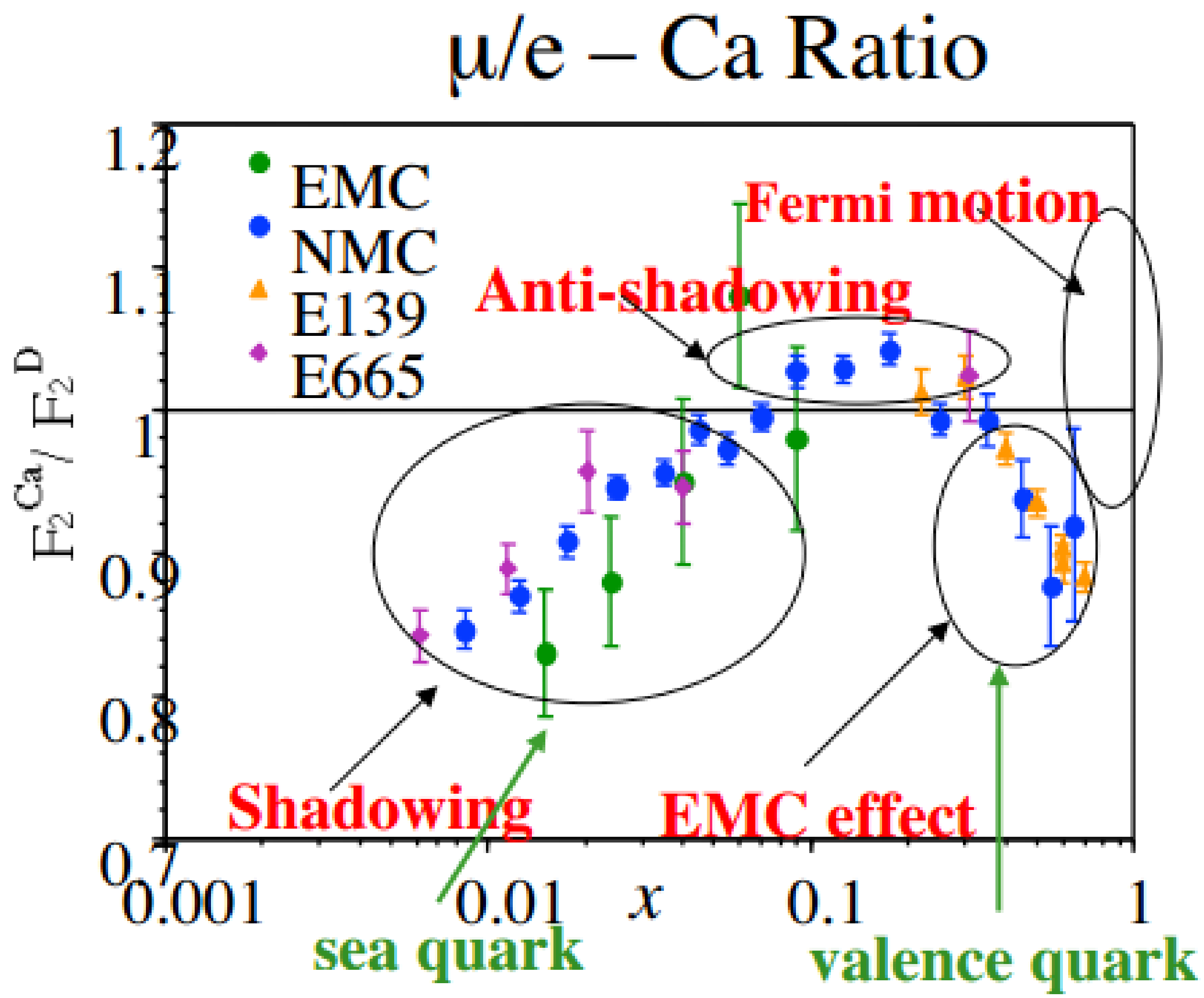
- Muon track charge matched in MINOS as a μ+
- No additional tracks from the vertex



- Signal definition:
  - QE-like: defined by particles exiting the nucleus
  - Any number of neutrons and only low-energy protons (below 120 MeV kinetic energy)
  - No pions, heavy baryons etc
  - Additional constraint: muon angle <20 degrees because of the MINERvA-MINOS acceptance

Studies of Nuclear Effects with Neutrinos

- Reminder: F2/nucleon changes as a function of A. Measured in μ/e - A not in nu-A



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

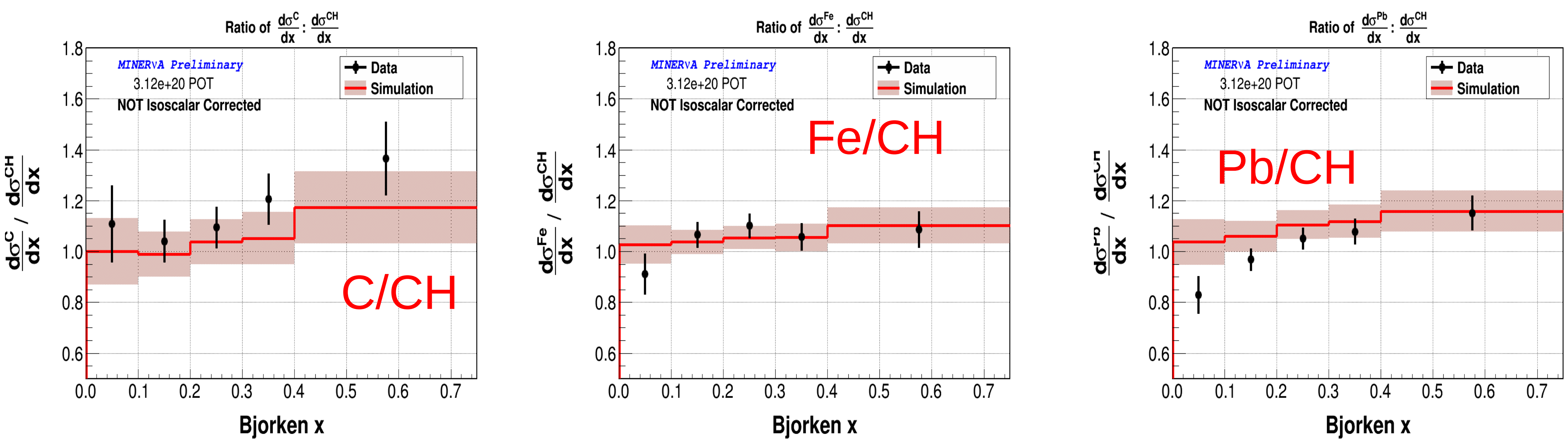
Scaling variable Bjorken x. In the parton model, x is the fractional momentum of the struck quark

-

Fermilab

Deep Inelastic Scattering from MINERvA

- MINERvA produced deep inelastic ratios from nuclear targets to study x dependent nuclear effects
- 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



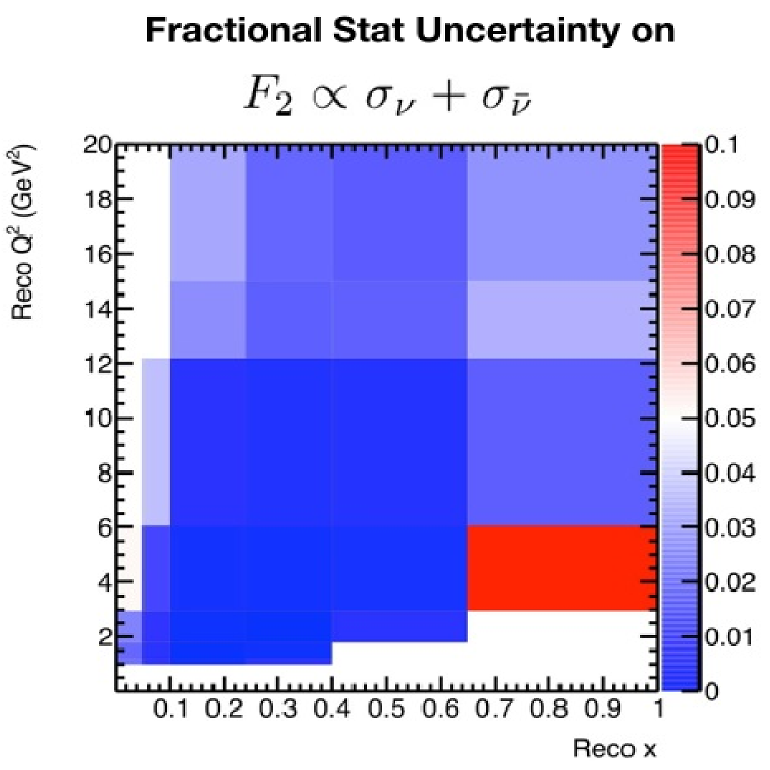
- The data suggest additional nuclear shadowing in the lowest x bin (0<x<0.1) than predicted in lead, it is at a value of x and Q2 where shadowing is not normally found in charged lepton nucleus scattering
- In the MEC region (0.3<x<0.75), we see good agreement between data and simulation

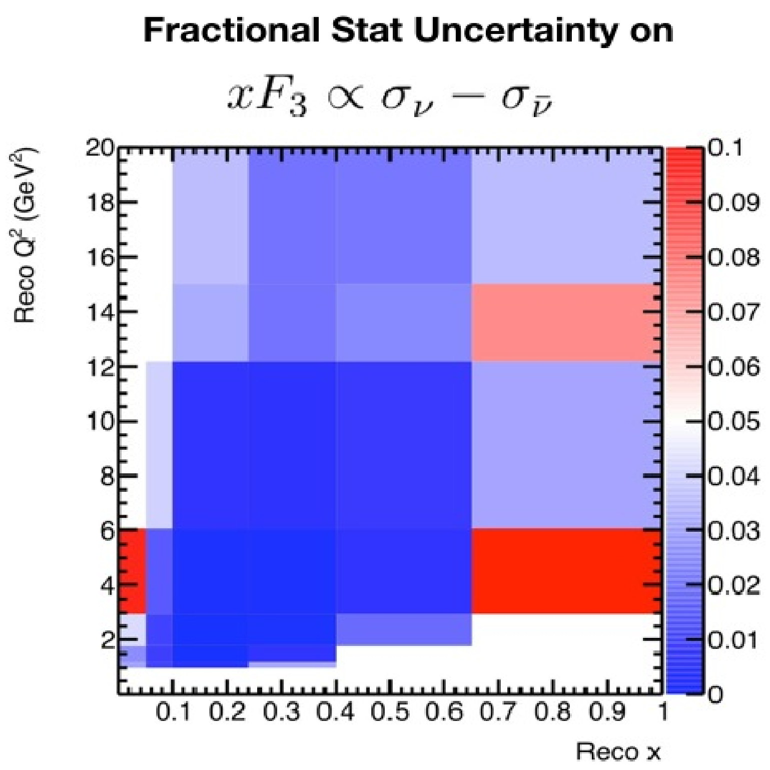
Structure Function Extraction at MINERvA

- MINERvA is collecting data using a medium energy beam <E>=5GeV. This data set will be used to extract the nuclear structure functions for neutrinos

$$\frac{d^2\sigma^{\nu(\bar{\nu})A}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)}\left[\frac{y^2}{2}2xF_1^{\nu(\bar{\nu})A} + \left(1 - y - \frac{Mxy}{2E_\nu}\right)F_2^{\nu(\bar{\nu})A} \pm y\left(1-\frac{y}{2}\right)xF_3^{\nu(\bar{\nu})A}\right]$$

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





12E20 POT Exposure

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