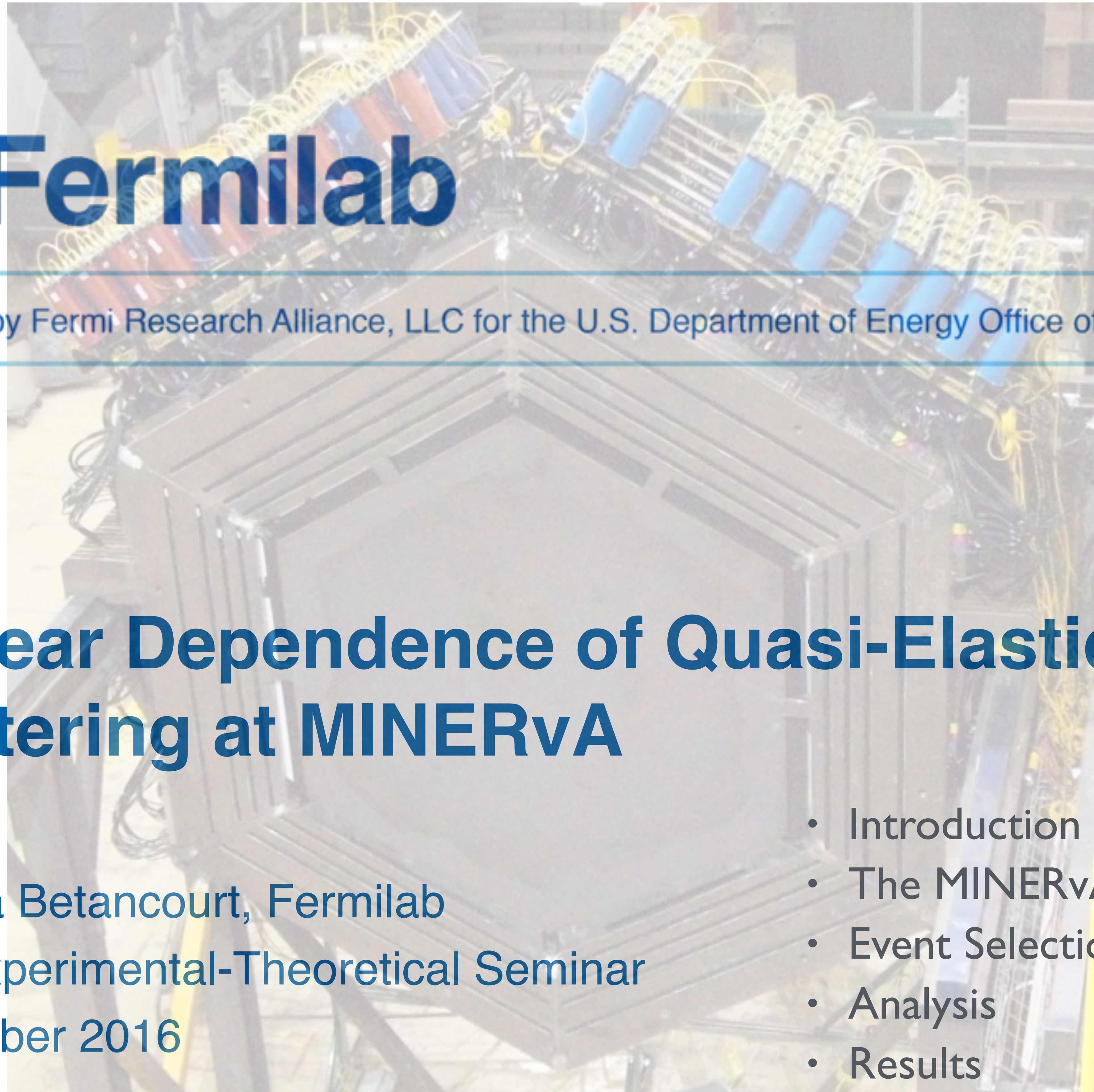


Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Nuclear Dependence of Quasi-Elastic Scattering at MINERvA

Minerba Betancourt, Fermilab

Joint Experimental-Theoretical Seminar

07 October 2016

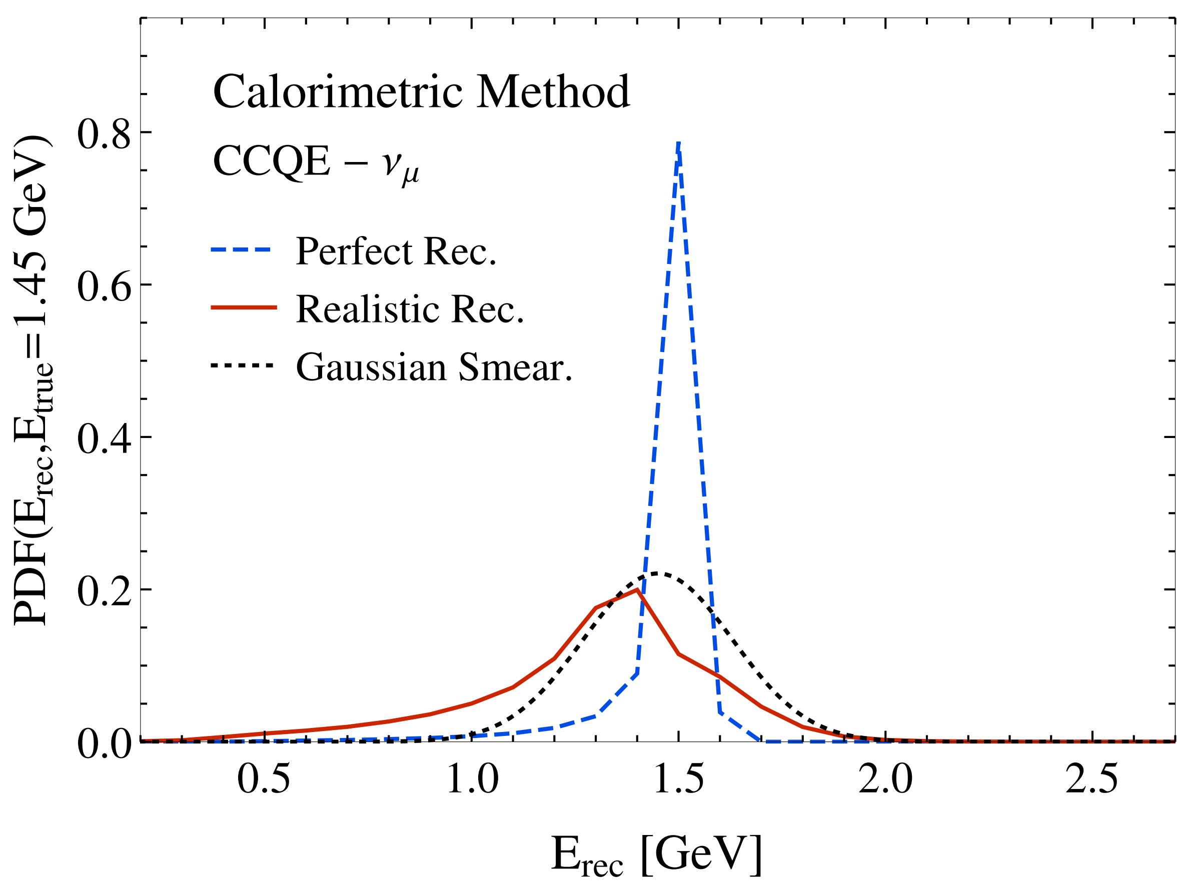
- Introduction
- The MINERvA experiment
- Event Selection
- Analysis
- Results

Motivation

- Neutrino interactions are very poorly understood. This has a direct impact in neutrino oscillation experiments
- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely

Motivation

- Neutrino interactions are very poorly understood. This has a direct impact in neutrino oscillation experiments
- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely
- Some experiments use the lepton kinematics only, other experiments use the hadronic energy as well
- A nice example: Probability distribution functions for an event of energy E_{true}=1.45 GeV to be reconstructed at an energy E_{reco}



A. M. Ankowski, O. Benhar, P. Coloma, P. Huber, C.-M. Jen, C. Mariani, D. Meloni, and E. Vagnoni Phys. Rev. D 92, 073014

Distributions are asymmetric due to pion absorption in the nuclear medium and the energy carried out by neutron

Motivation

- Neutrino oscillation experiments measure:

Events at the Near Detector $\phi \times \sigma \times \epsilon \times$ **Nuclear Effects**

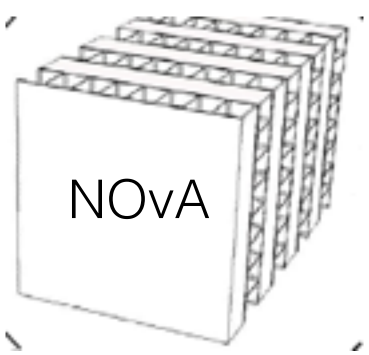
Events at the Far Detector $\phi' \times \sigma \times \epsilon \times$ **Nuclear Effects** $\times P_{\nu_\mu \rightarrow \nu_e}$

- Having near and far detectors helps reduce some systematics
- Since the flux is different at the near compared to the far detector due to geometry and oscillation, the convolution of flux, cross section, and nuclear effects are different
- We still need a nuclear model to convert from produced to detected energy spectrum and topology in the near and the far detectors

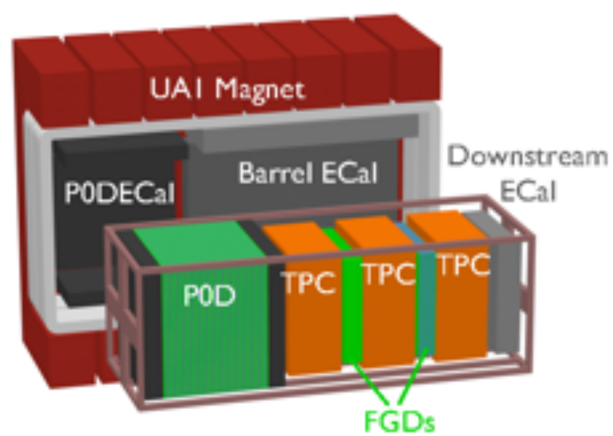
Modern Neutrino Experiments

- Modern neutrino experiments using neutrinos from accelerators
  - Different detector technologies
  - Detectors made with different targets: carbon, liquid argon, helium, iron..
- We need to model nuclear effects on a range of nuclei

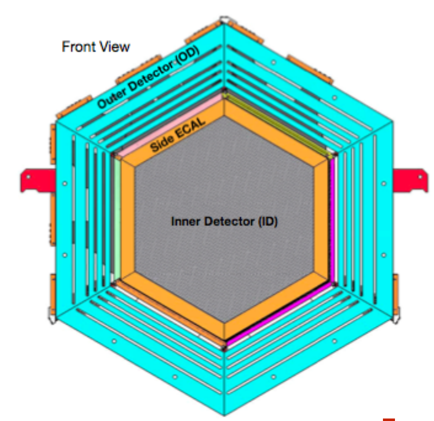
Carbon



T2K

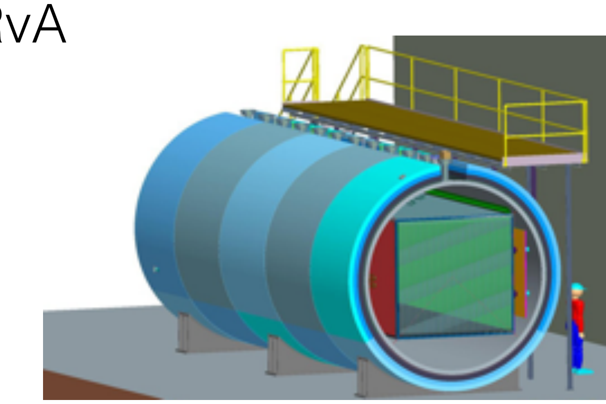


MINERvA



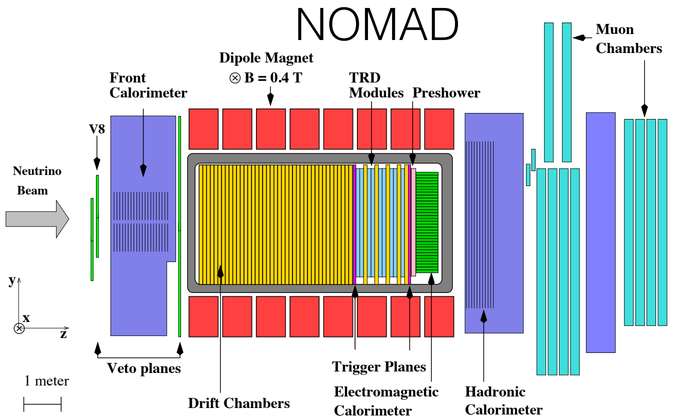
Liquid Argon

MicroBooNE

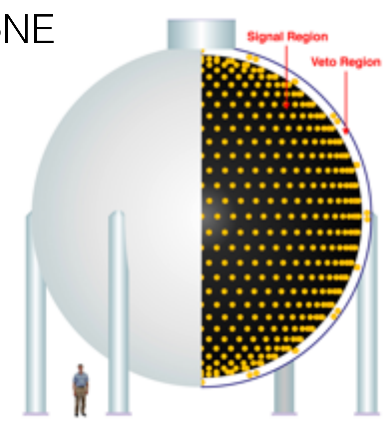


Iron

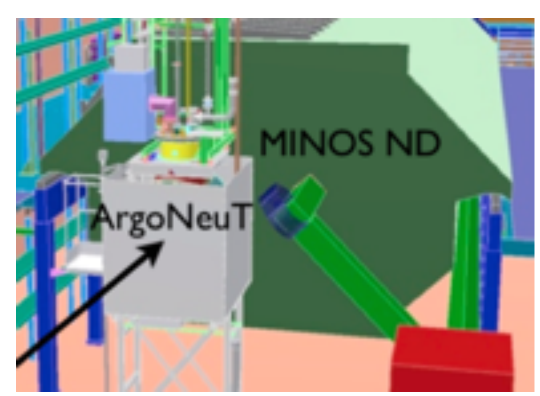
NOMAD



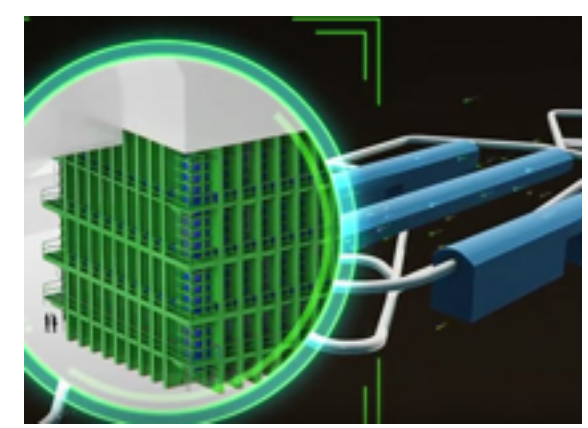
MiniBooNE



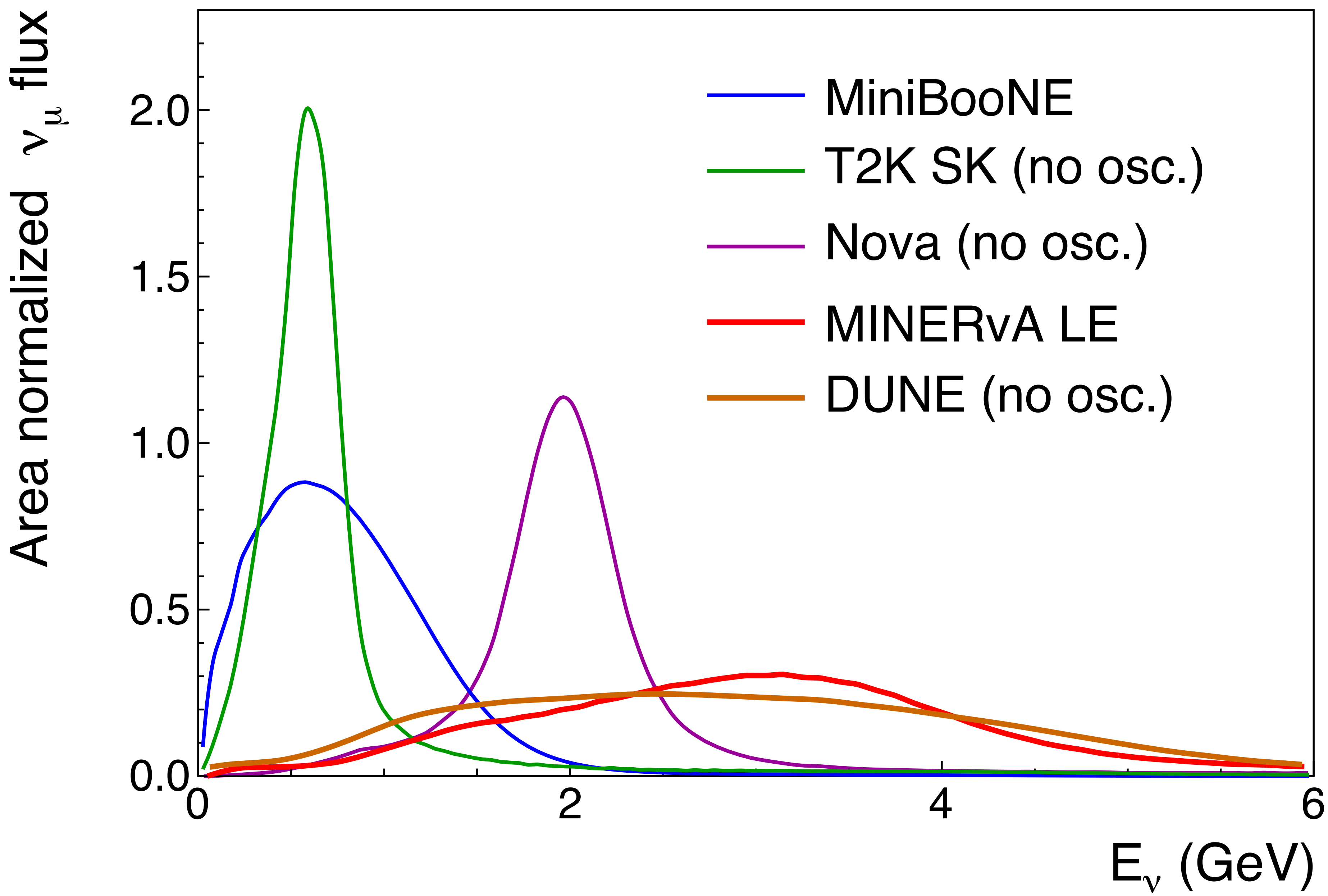
ArgoNeuT MINOS



DUNE



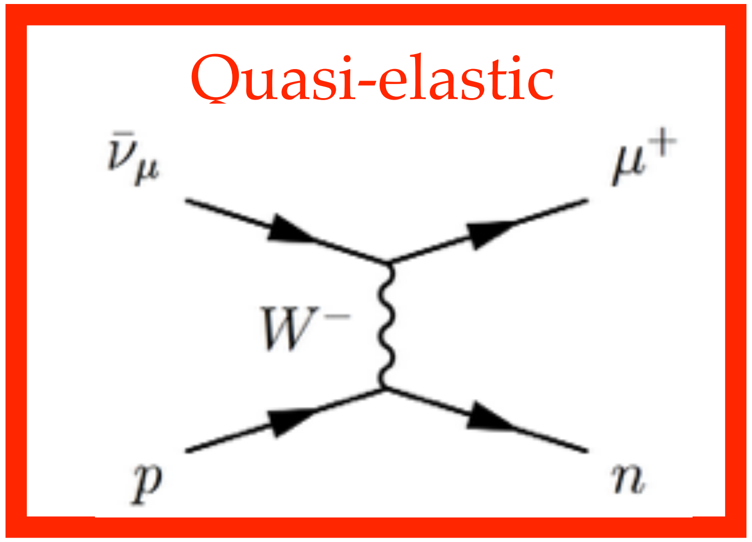
Neutrino Energies for Different Experiments



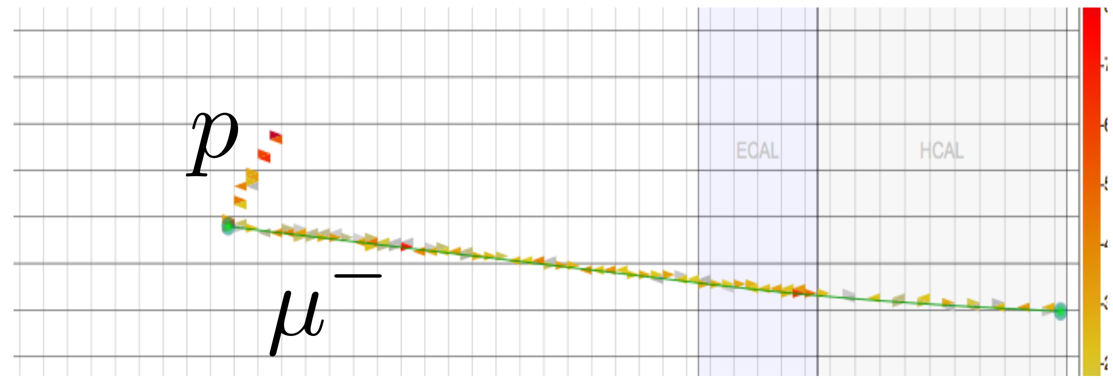
- MINERvA flux covers most of the DUNE flux

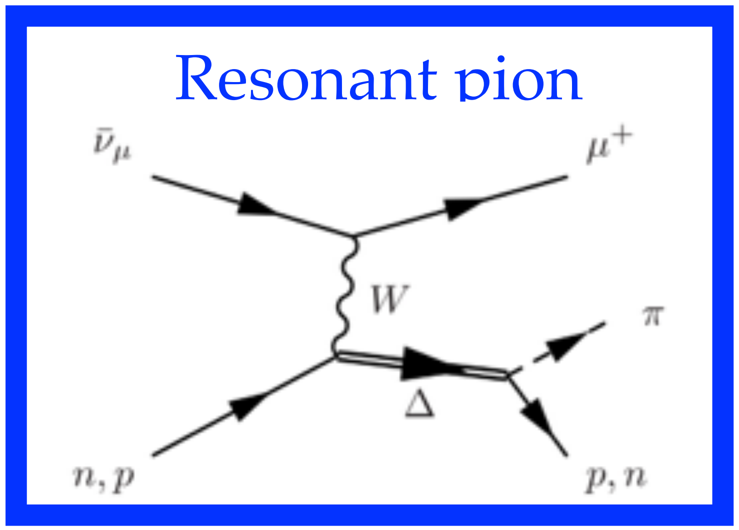
Plot courtesy of Phil Rodrigues

Charged Current Interactions

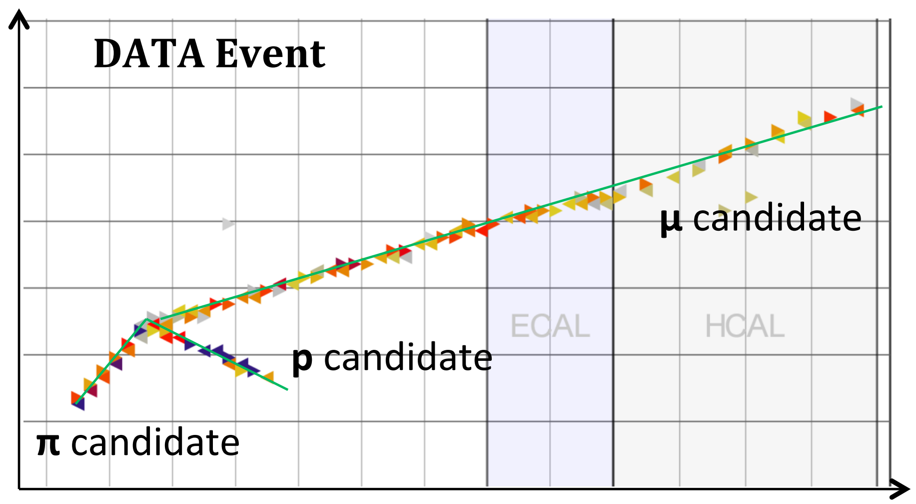


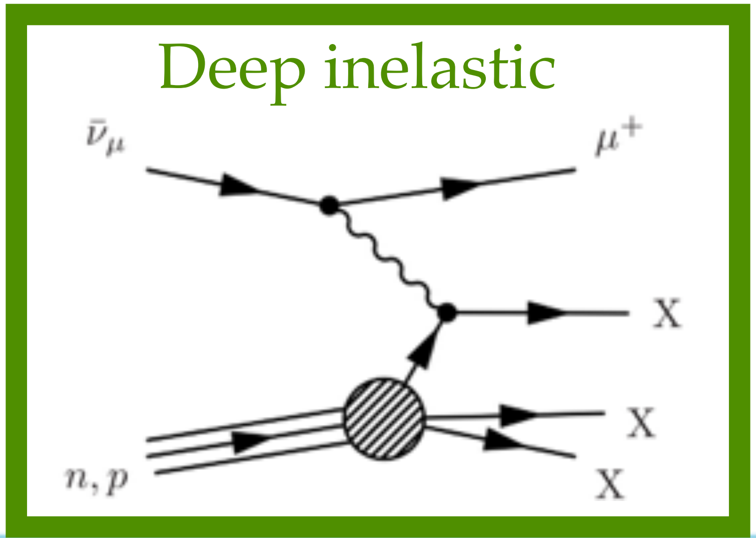
QE



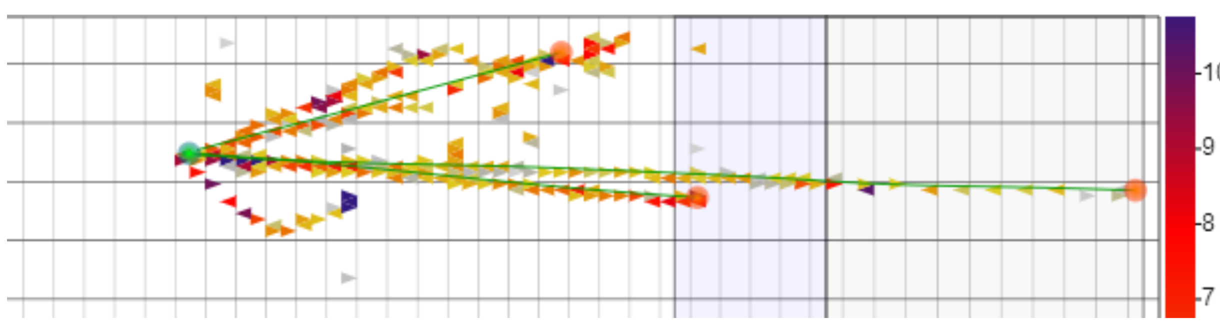


RES

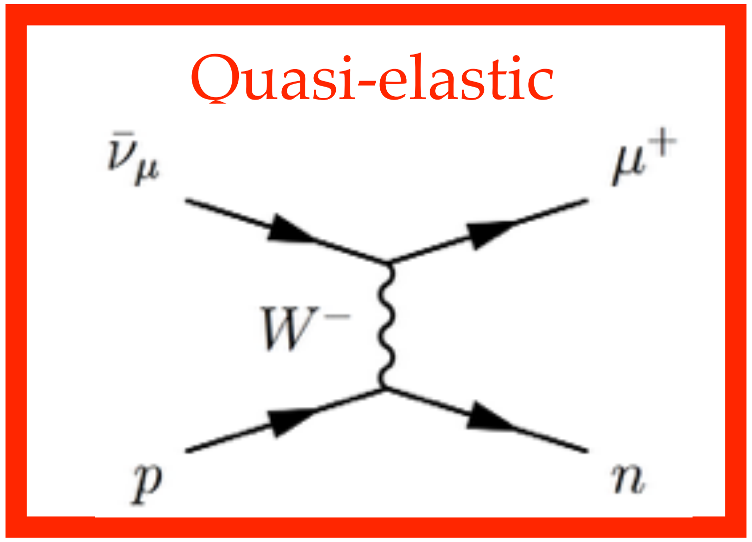




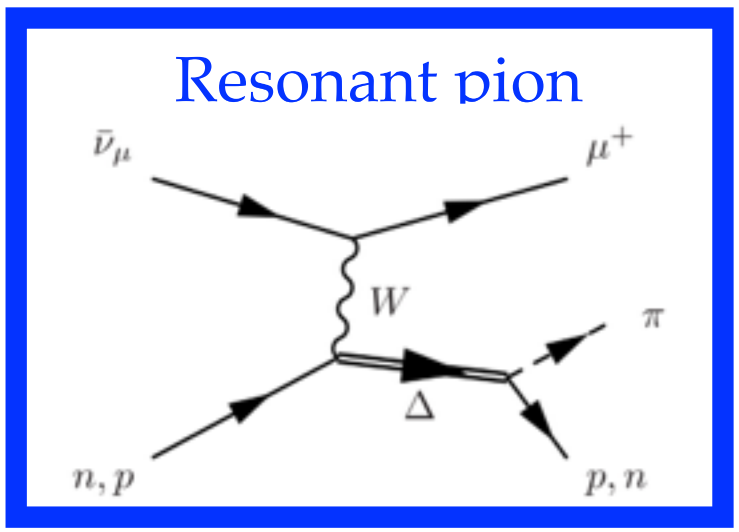
DIS



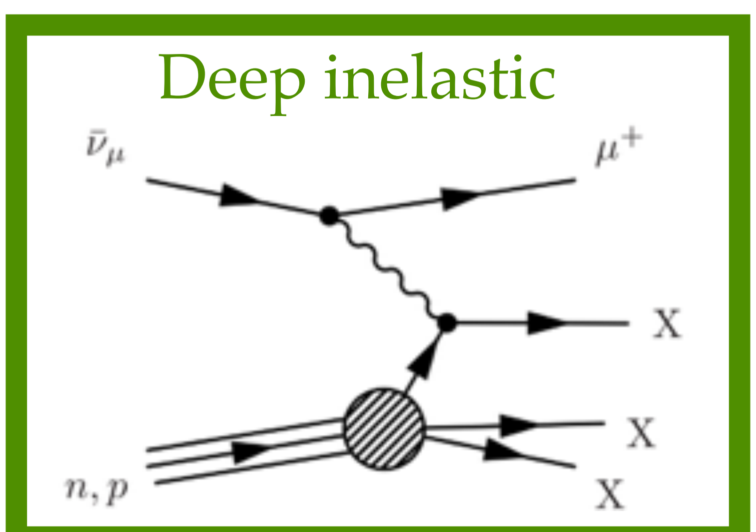
Charged Current Interactions



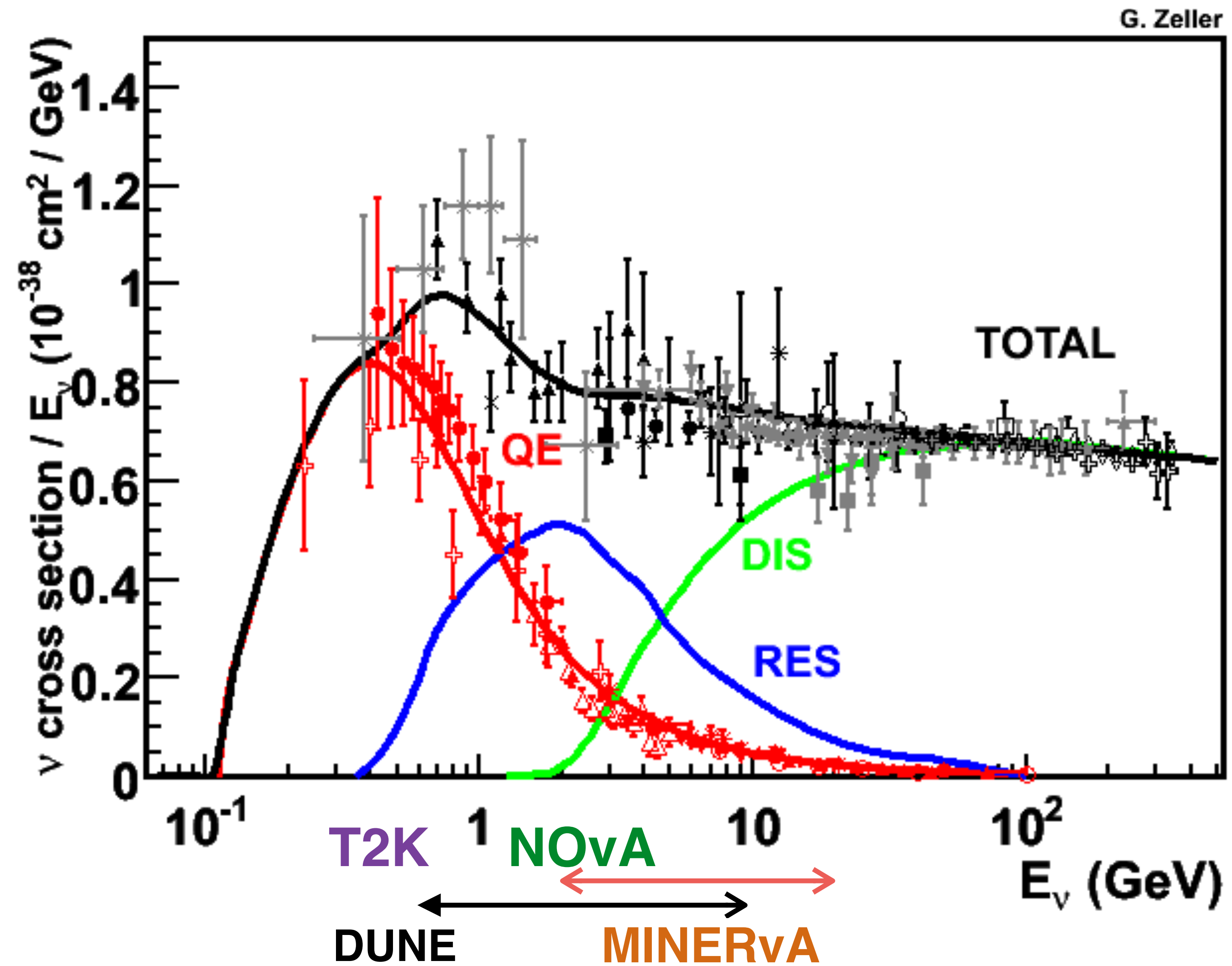
QE



RES



DIS

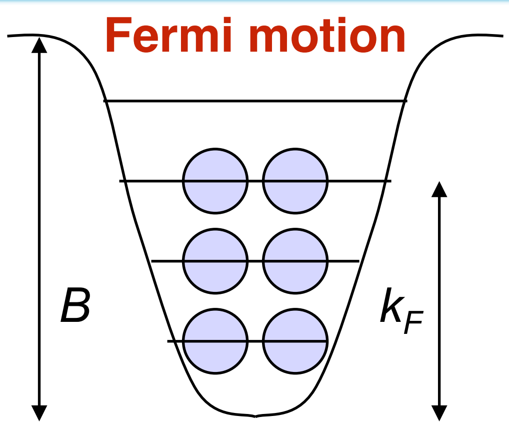


J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Fermilab

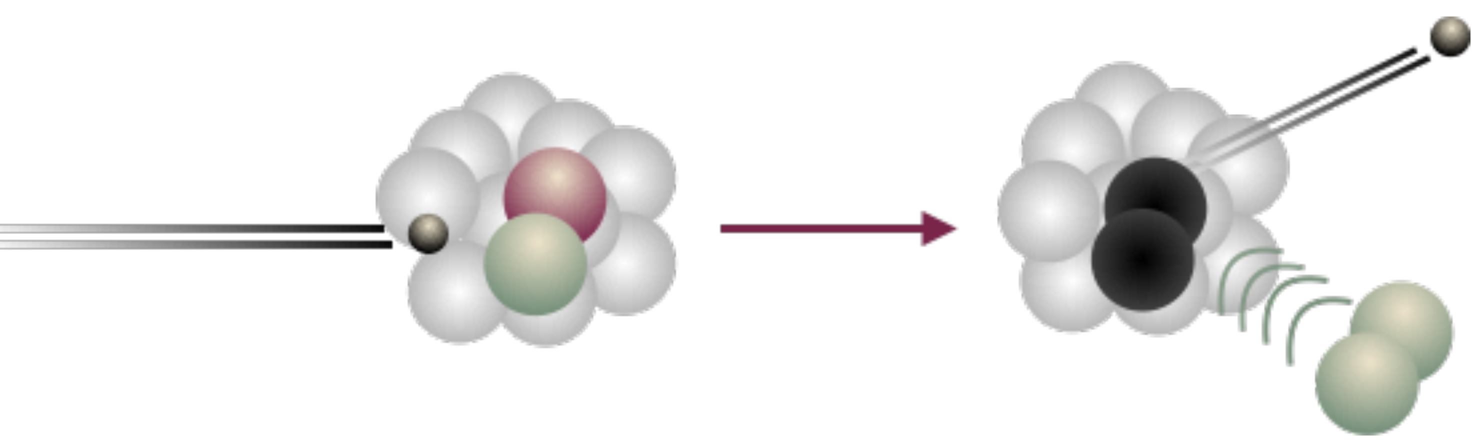
Nuclear Effects

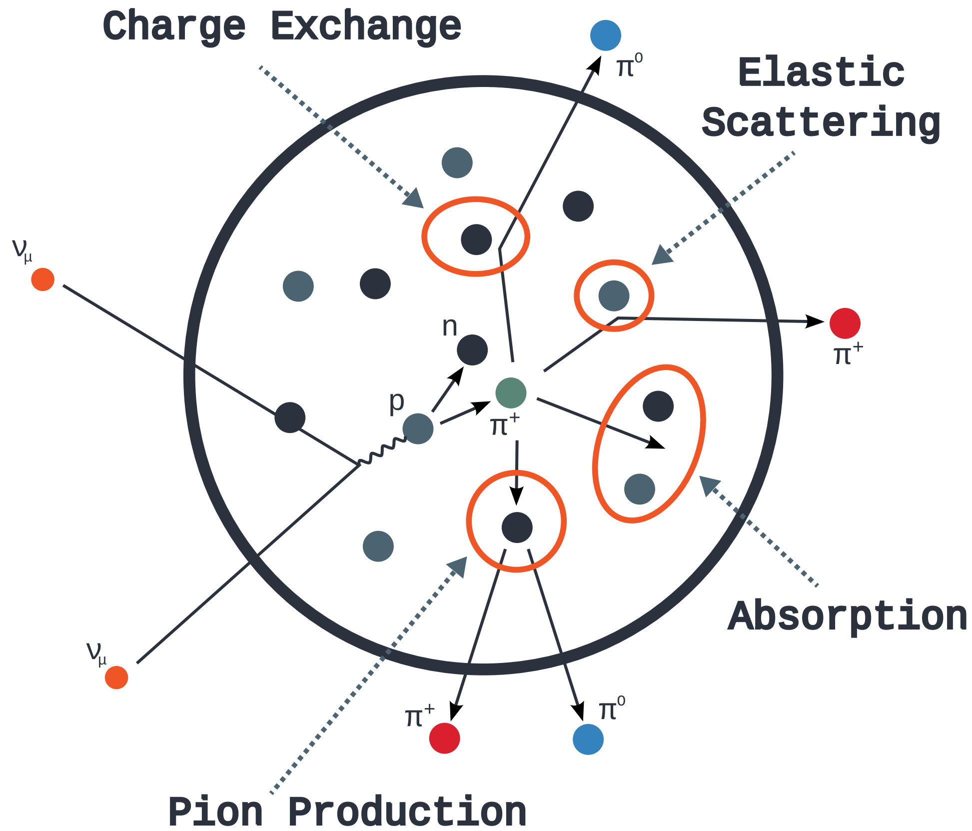
- Fermi motion: In a nucleus, the target nucleon has a momentum. Modeled as Fermi gas that fills up all available state until some Fermi momentum
- Pauli blocking: Pauli exclusion principle ensures that states cannot occupy states that are already filled
- Multi nucleon interactions
- Final state interactions



Final State Interactions (FSI)

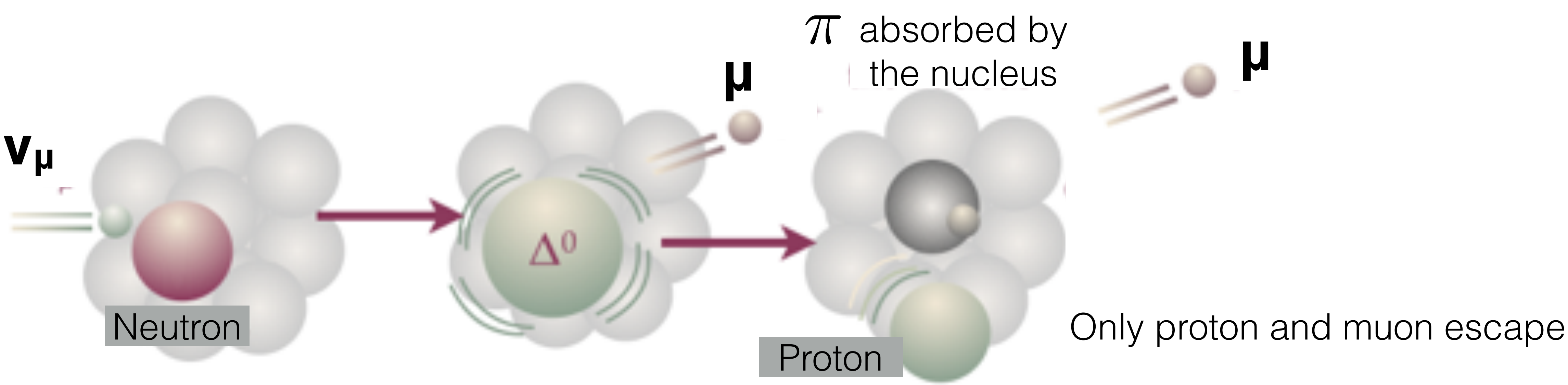
Multi nucleon interactions





Why We Need to Understand Nuclear Effects

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- An example of nuclear effects:

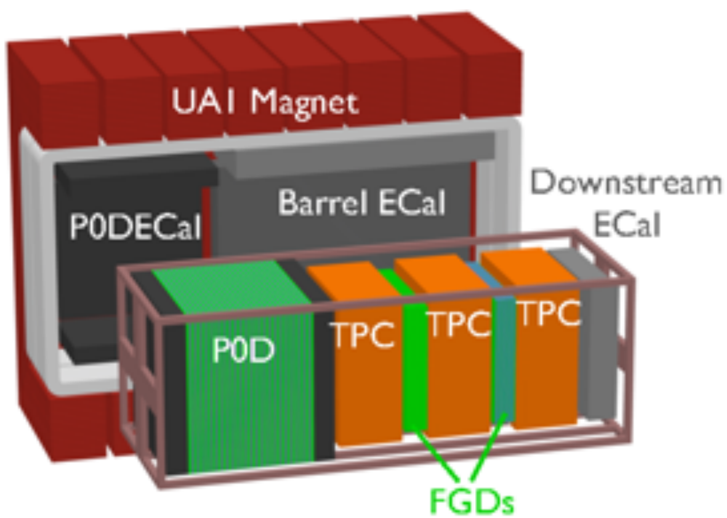


- Due to final state interactions, particles can interact with nucleons and pion can be absorbed before exiting the nucleus

Why We Need to Understand Nuclear Effects

- Plus if the near and far detector are made of different materials, we need to worry about A dependence of nuclear effects
- For example, T2K uses near detector carbon measurements even though the far detector is made of water

T2K Near Detector

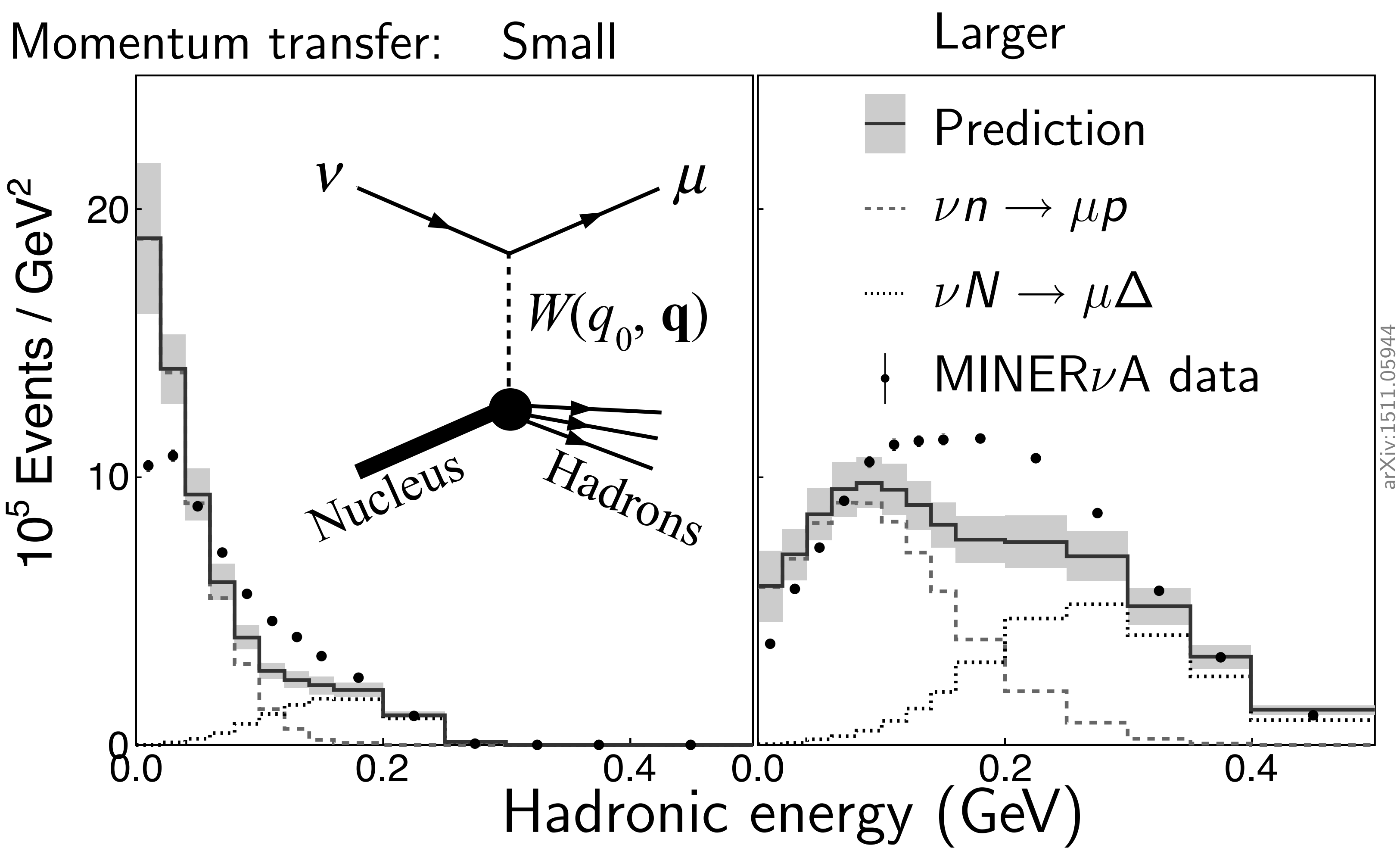


T2K Far Detector

- DUNE near detector final design might include a target different than the far detector?

Nuclear Models and Data

- Recent experimental data is not well described by current nuclear models
- For example, recent data from MINERvA compared with simulations

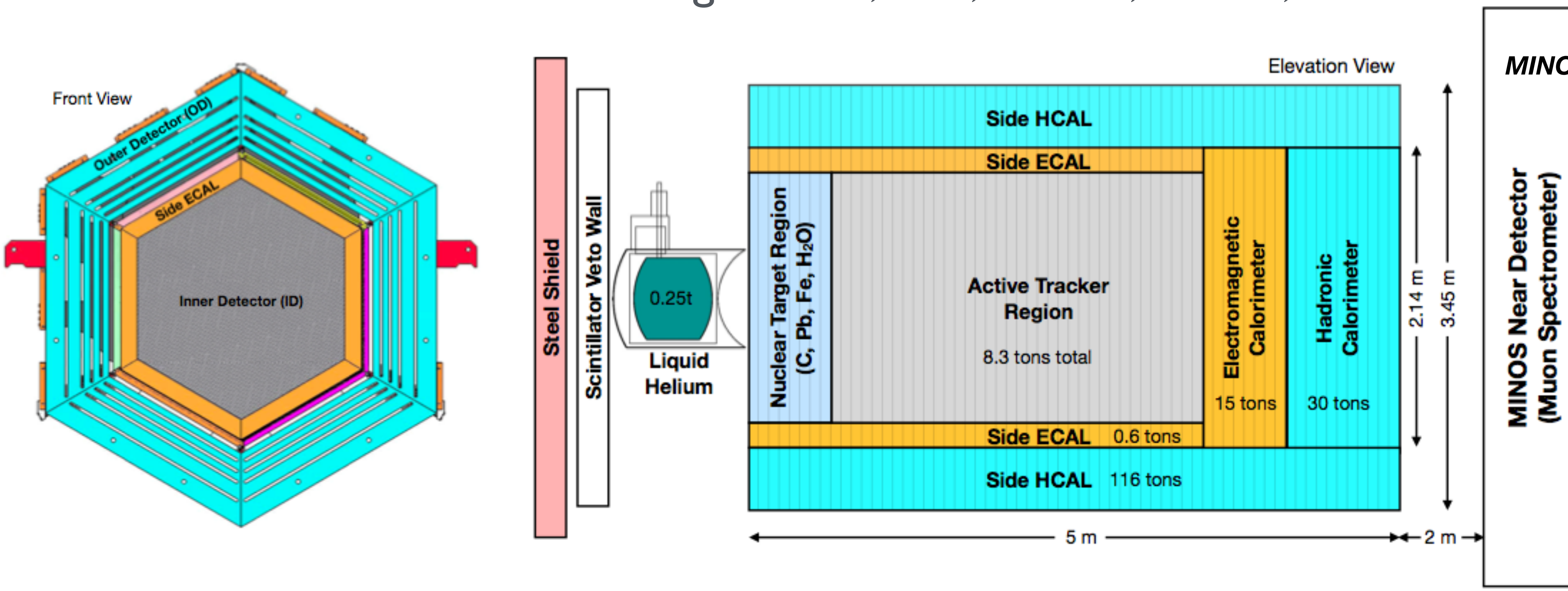


Phys. Rev. Lett. 116 (2016) 071802

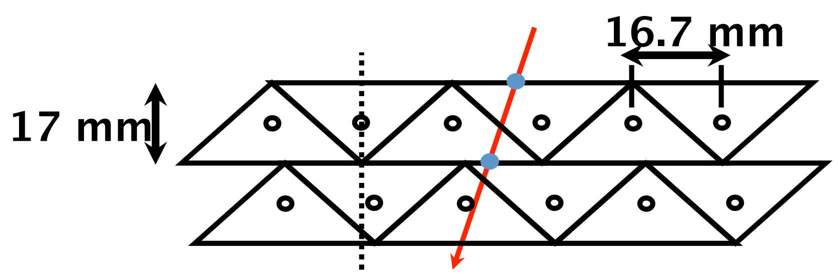
- It is crucial to have a reliable nuclear model in the Monte Carlo generator to take detector quantities back through the nucleus to produced quantities
- Understanding neutrino interactions with nuclei is vital for precision oscillation measurements

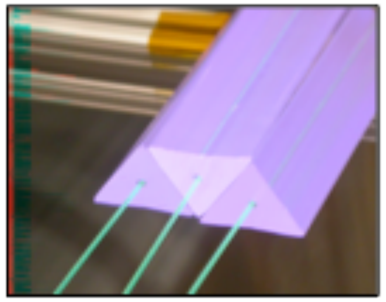
Studying Nuclear Effects in MINERvA

- Fine-grained scintillator tracker surrounded by calorimeters
- MINERvA has different nuclear targets iron, lead, carbon, helium, and water



Thanks to MINOS





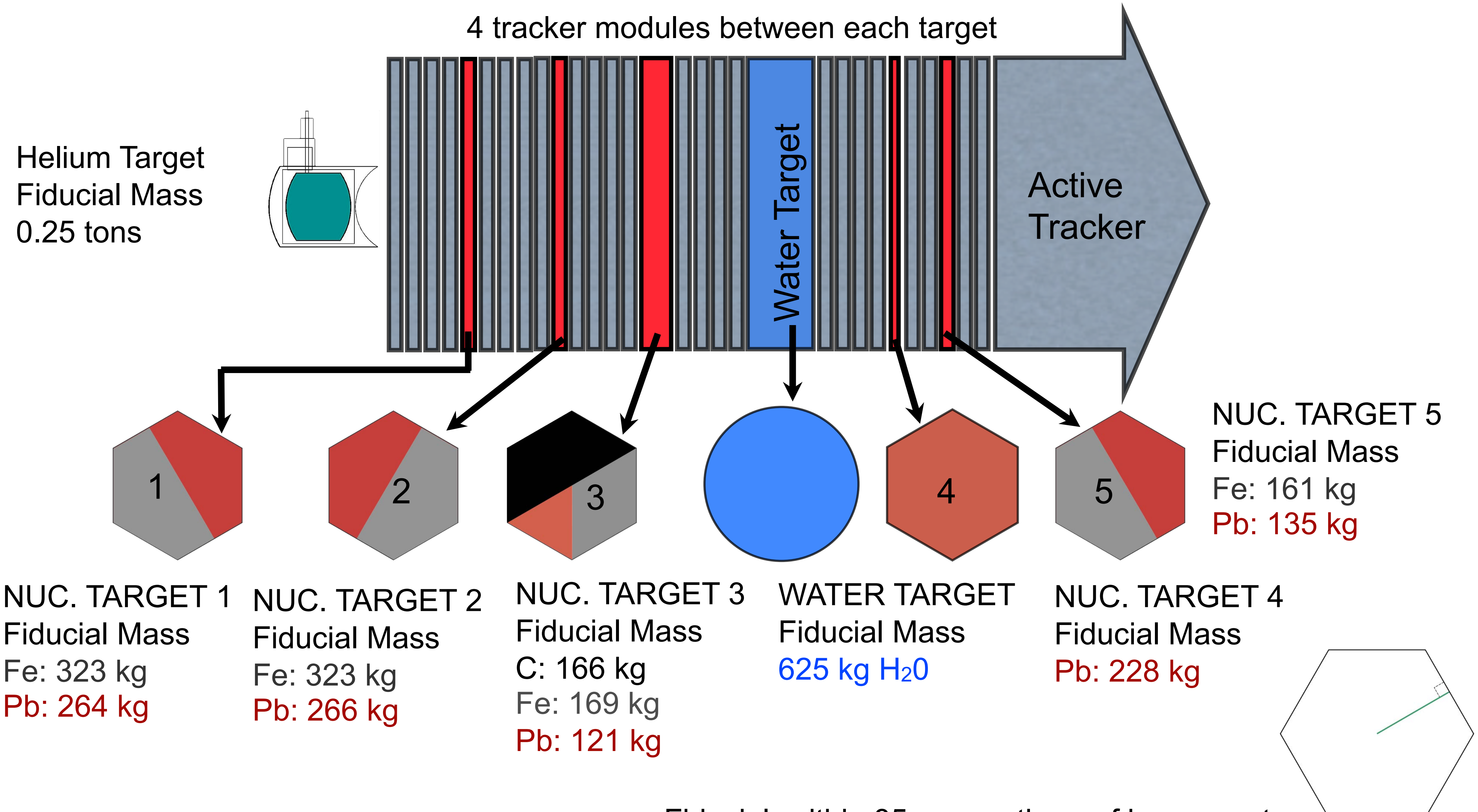
Three views of scintillator bars give unambiguous 3D track reconstruction

Design, calibration, and performance of the MINERvA detector

Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

Nuclear Targets

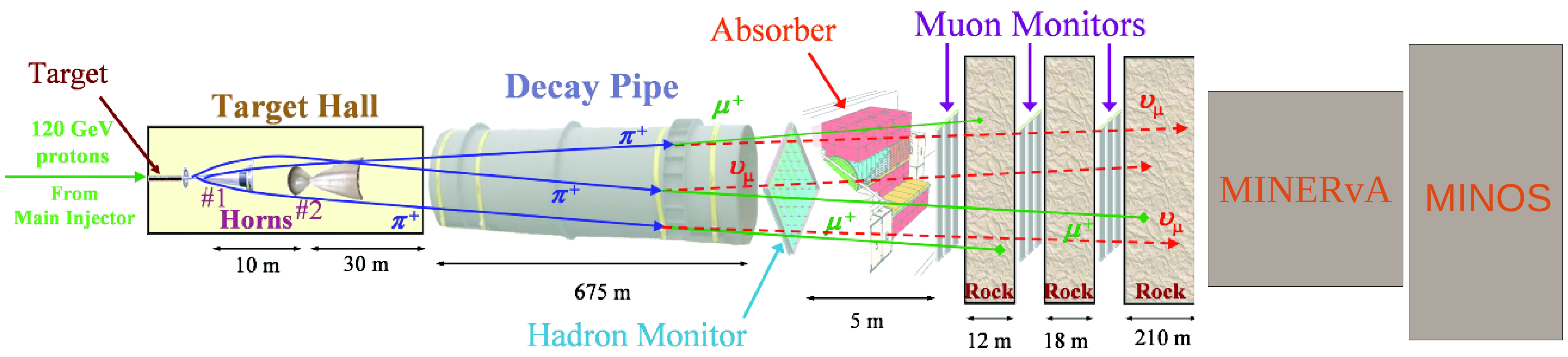
- Different targets built with combinations of different materials



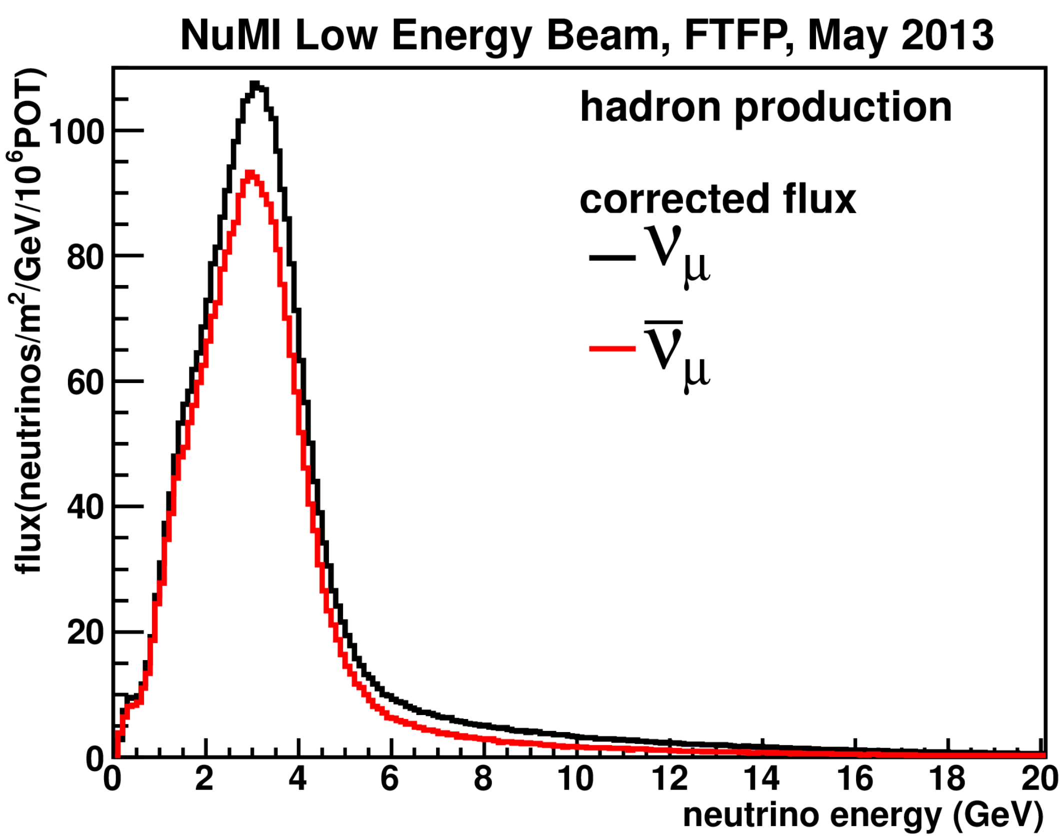
Fiducial: within 85 cm apothem of beam spot

Carbon Iron Lead CH

Neutrinos from NuMI Beamline



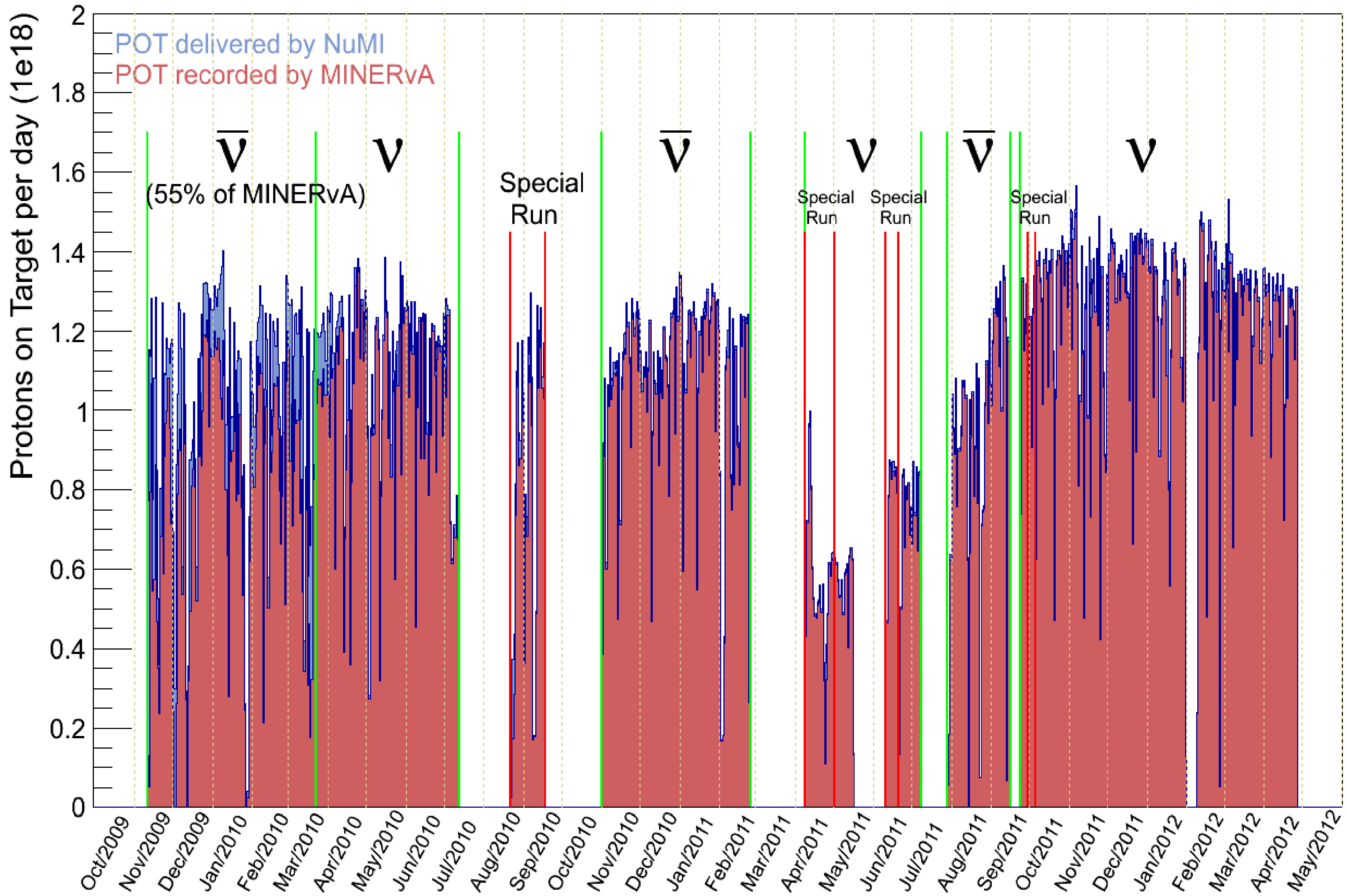
- 120 GeV protons from the Fermilab Main Injector hit a 1m graphite target, producing kaons and pions
- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra
- Presenting results for the low energy beam
- MINERvA is currently running with the medium energy beam



Data Set

- Today's analysis uses 3.06E20 POT of neutrino data

Thanks to the accelerator division

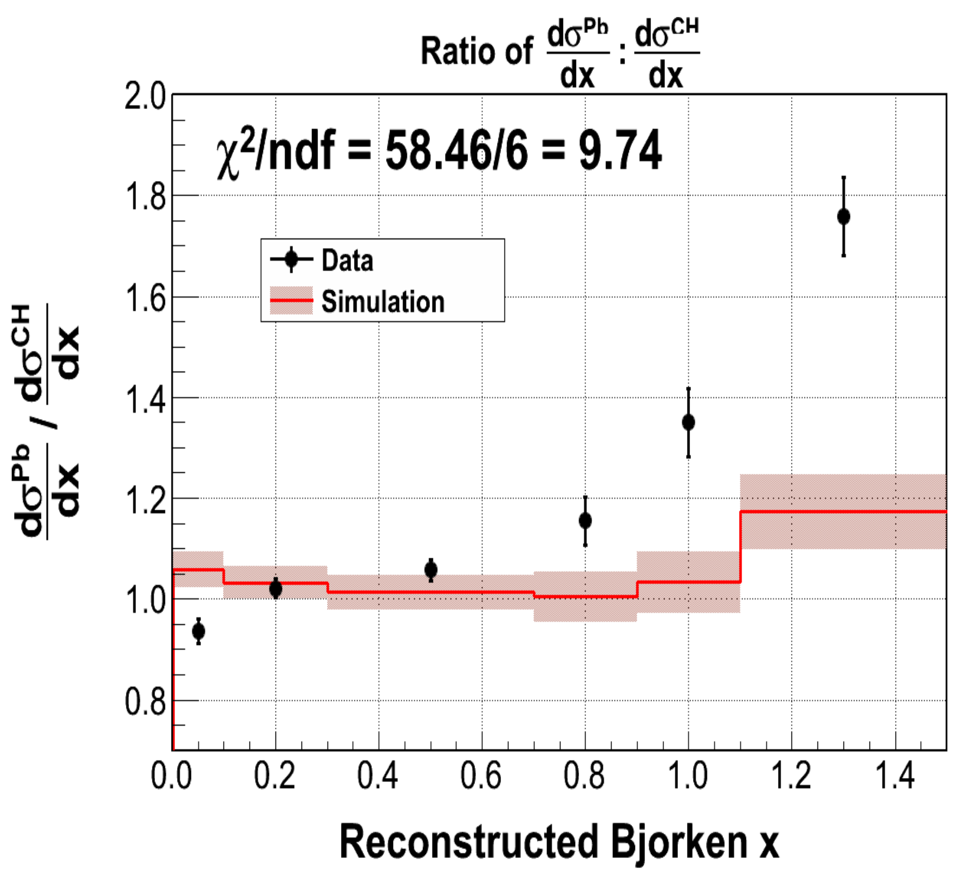


Fermilab

Direct Measurements of Nuclear Effects

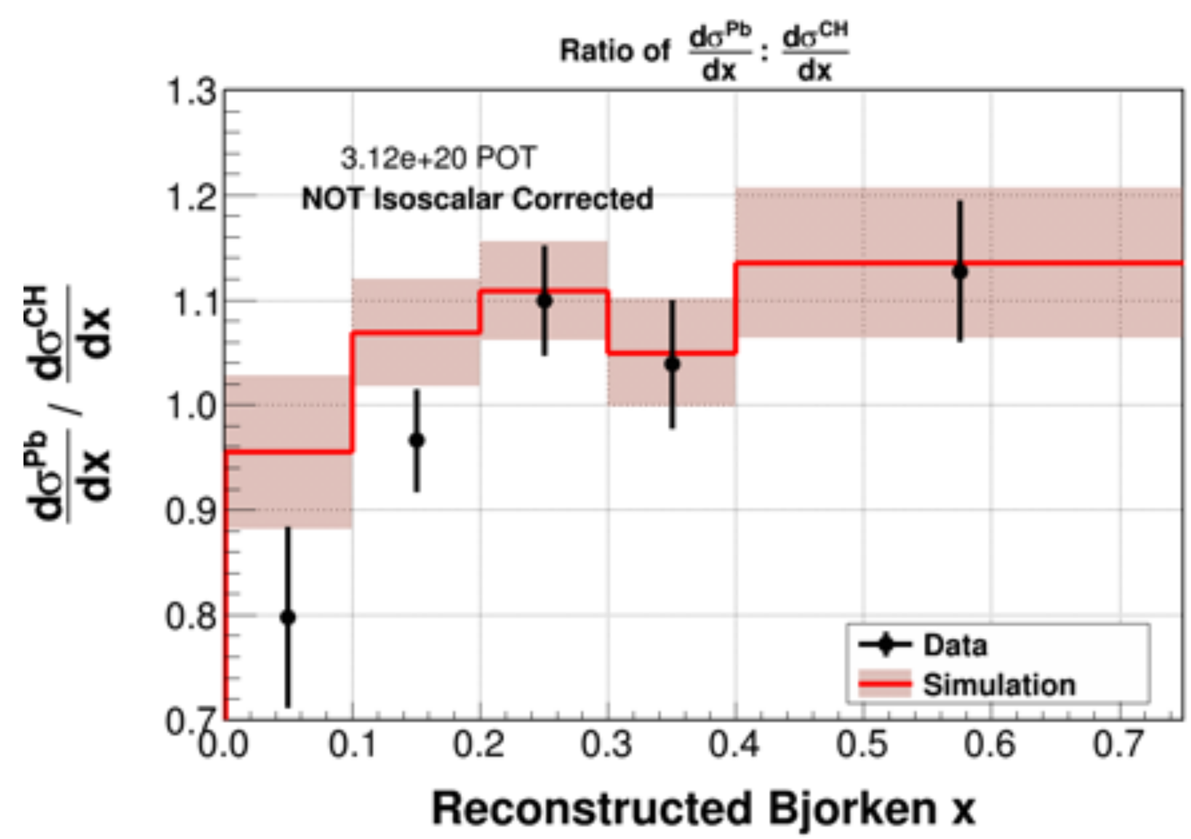
- MINERvA has looked at nuclear effects in inclusive and DIS processes
- Ratios of cross sections as a function of Bjorken x $x = \frac{Q^2}{2ME_{had}}$

Inclusive lead to scintillator



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

DIS lead to scintillator

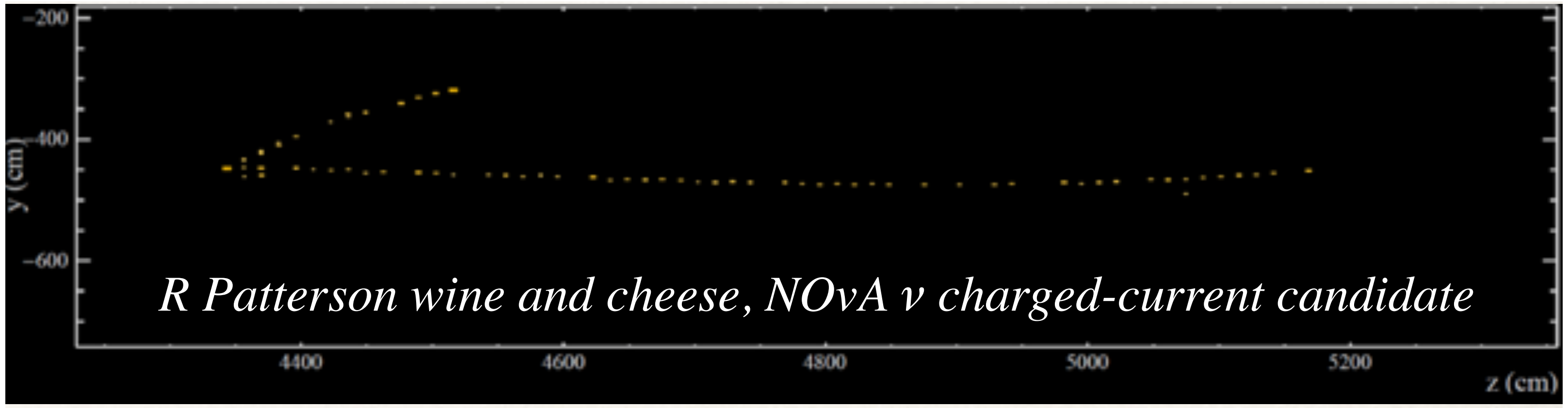


Phys. Rev. D 93, 071101 (2016)

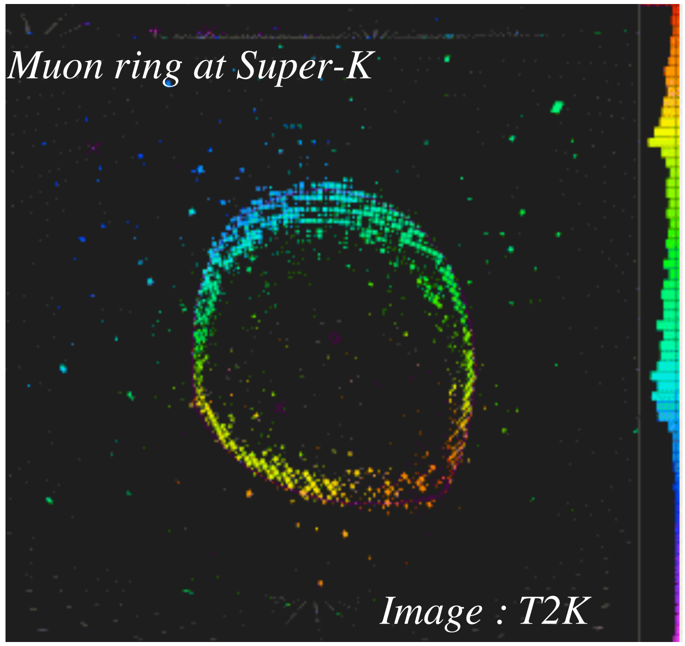
- Oscillation experiments need to understand the nuclear effects for quasi-elastic and resonance too, not just the inclusive and DIS

Quasi-Elastic Scattering (CCQE)

- The Quasi-elastic process gives the largest contribution for the signal in many oscillation experiments
- We are using heavy targets for oscillation experiments, such as carbon and liquid argon
- Using heavy targets involves modeling nuclear effects
- As an example, a produced resonance interaction of energy E can be detected as quasi-elastic like candidate of energy E' if the pion is absorbed before leaving the nucleus
- The QE selection varies from experiment to experiment, some experiments use only the muon and others use the proton and muon



R Patterson wine and cheese, NOνA ν charged-current candidate



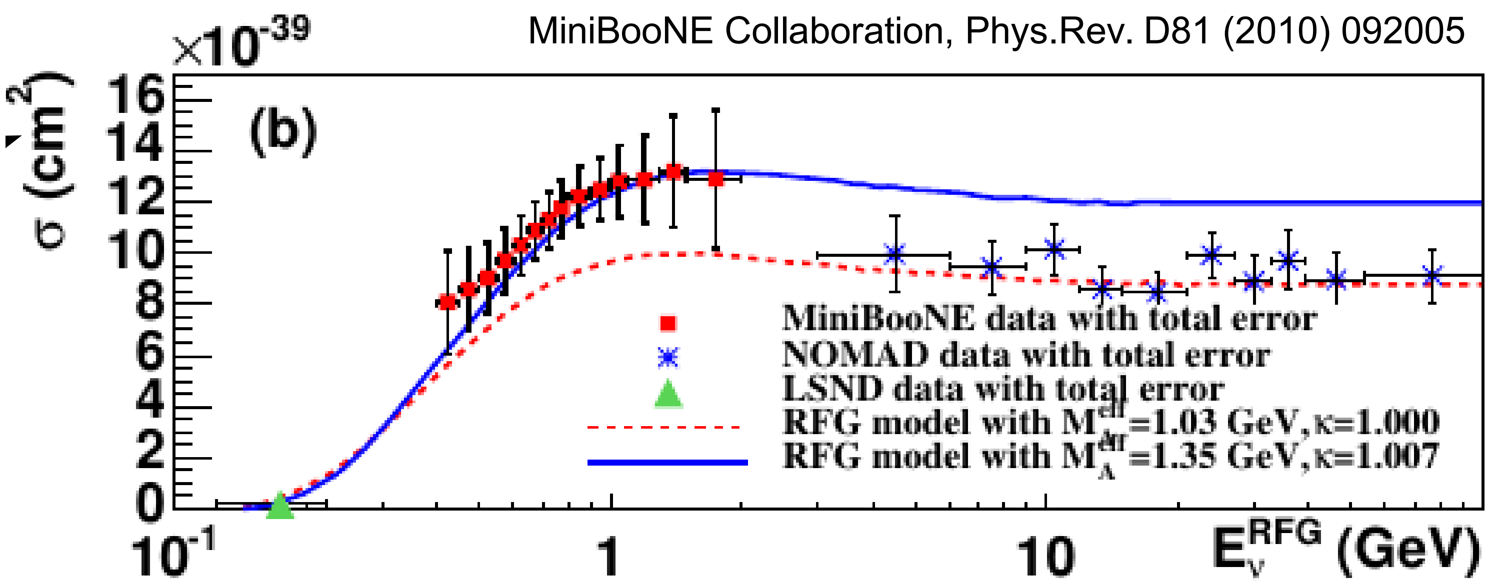
Muon ring at Super-K

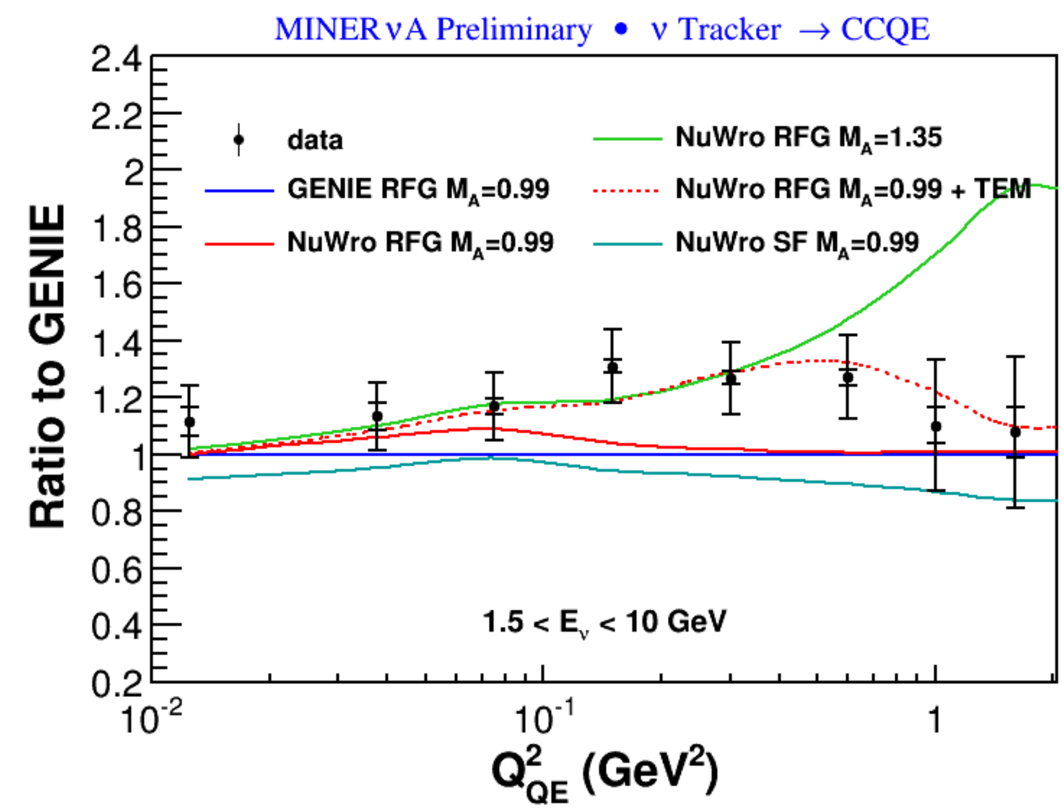
Image : T2K

Quasi-Elastic Scattering (CCQE) using the Muon Kinematics

- Quasi-elastic scattering has been measured using the kinematics of the muon and assuming the nuclear target is at rest
- The neutrino energy and four momentum transfer is reconstructed using the angle and momentum of the muon

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





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

- These measurements have told us a lot about models of CCQE, but they are limited because there are single measurements on single nuclei, and are measuring the superposition of cross section and nuclear effects

Quasi-Elastic Scattering using the Proton Kinematics

- At the beginning of last year, MINERvA published the first differential cross section as a function Q^2 determined from the proton, Tammy Walton's PhD thesis, Phys. Rev. D. 91, 071301 (2015)
- Q^2 is reconstructed using the leading proton from the event (different from the muon kinematic Q^2)
- Using the QE hypothesis and assuming scattering from a free nucleon at rest

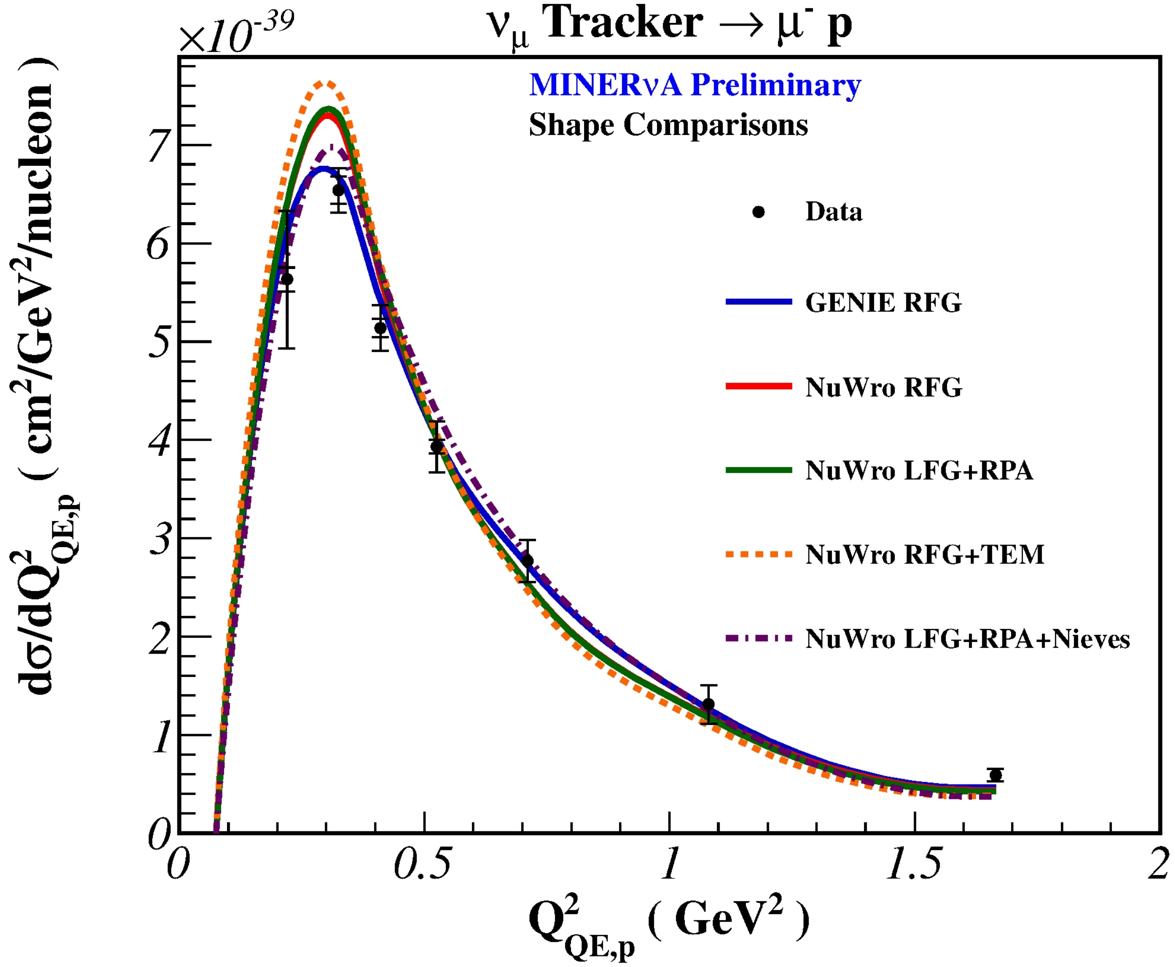
$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

- $M' = M_n - E_b$
- E_b is the binding energy
- T_p is the proton kinetic energy
- M_n is the mass of the neutron
- M_p is the mass of the proton

- Good news: we can use the proton to reconstruct the Q^2!

Quasi-Elastic Scattering using the Proton Kinematics

- Differential cross section as a function of the proton Q^2
- Using at least one proton with momentum >450 MeV/c



Phys. Rev. D. 91, 071301 (2015)

- Data was compared against different generators, the GENIE used was 2.6.2 and a earlier version of NuWro
- From the shape analysis, GENIE best describes the data
- The analysis I am presenting today is an extension of the earlier analysis, with a new event sample: the nuclear target region

Fermilab

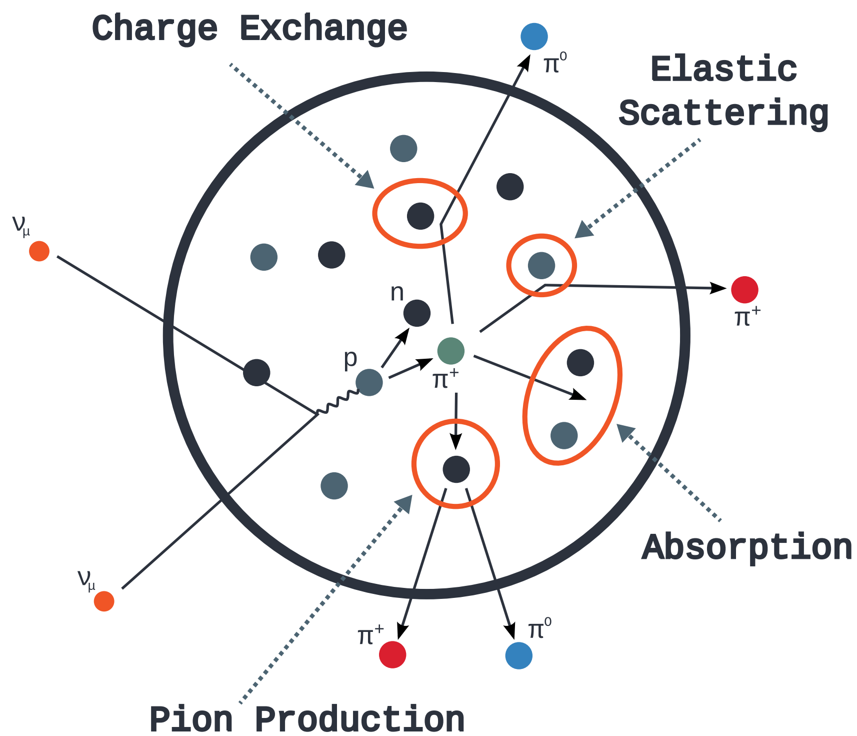
Simulations

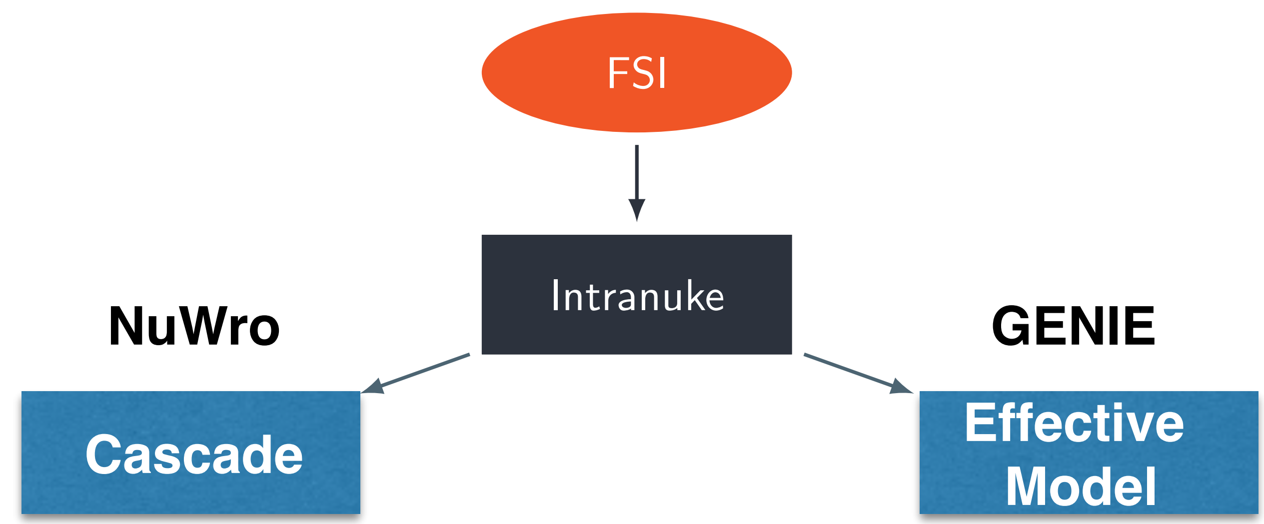
- We have made considerable progress in modeling neutrino interactions lately
- We use GENIE (2.8.4) Monte Carlo generator
- For detector response we use GEANT4 (4.9.2)
- Quasi-elastic scattering from nuclei is simulated using:
  - Relativistic Fermi Gas model with Bodek-Ritchie tail
  - Using the old 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

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

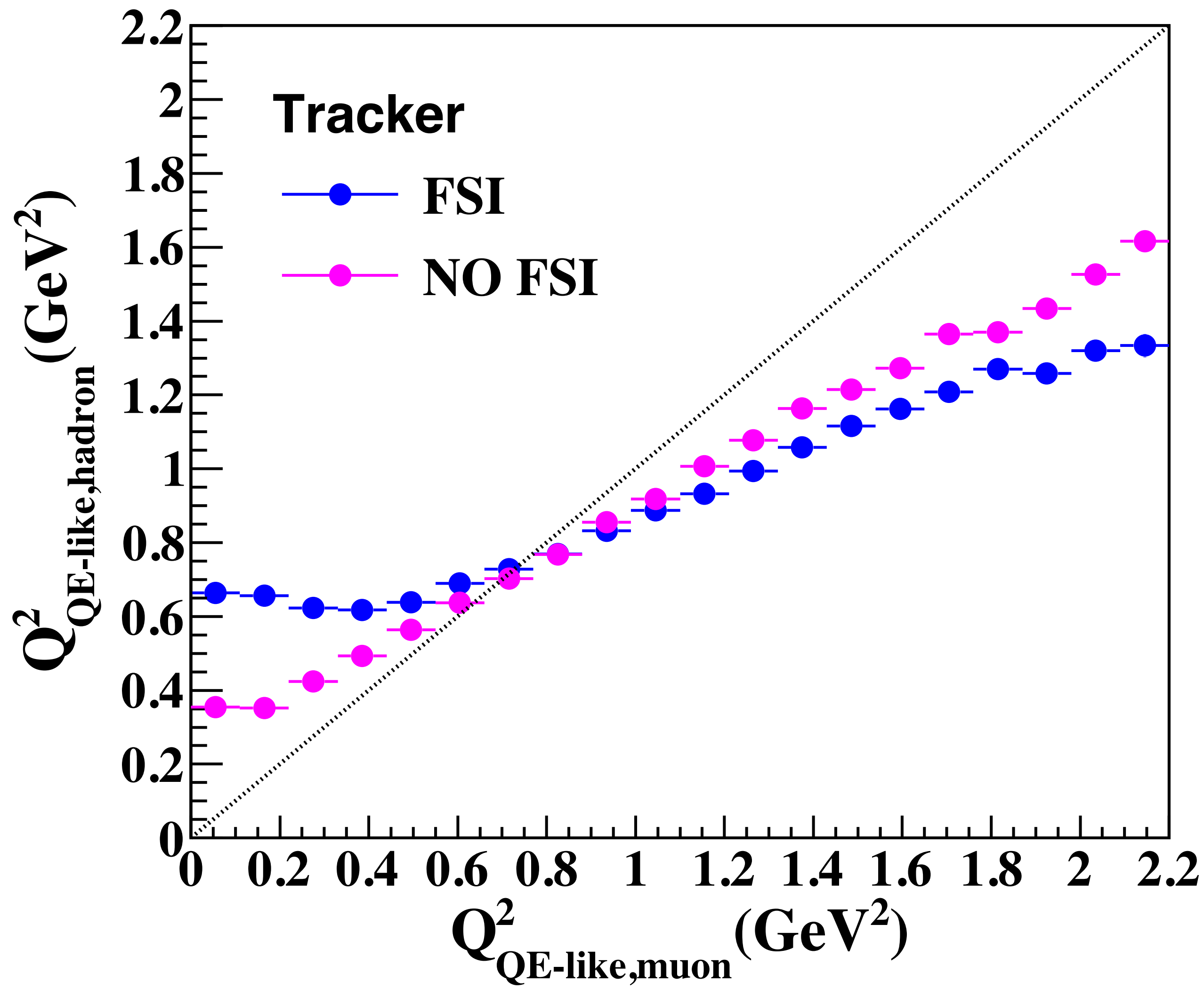
courtesy of Tomasz Golan

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

Reconstructed Muon Q^2 vs Proton Q^2 (Plastic)

- Comparing the Q^2 reconstructed from muon kinematics and the Q^2 reconstructed from proton kinematics

GENIE simulation



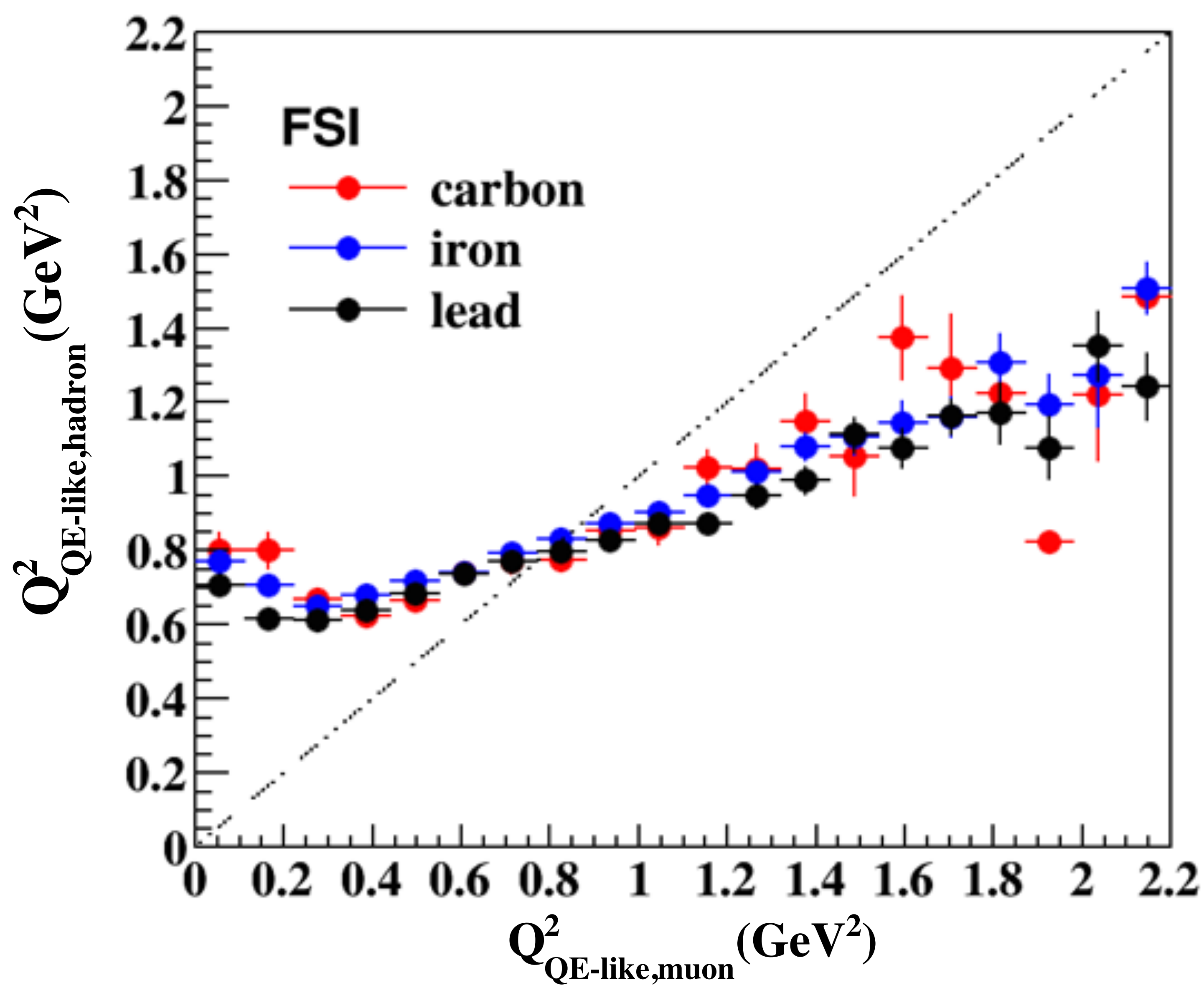
$$Q^2_{hadron} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

$$Q^2_{muon} = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

- Q^2 from proton kinematics is affected by final state interactions

Reconstructed Muon Q² vs Proton Q² (Different Nuclei)

- Comparing each of the nuclei we are going to measure



GENIE simulation

- Note that GENIE has similar FSI for different nuclei

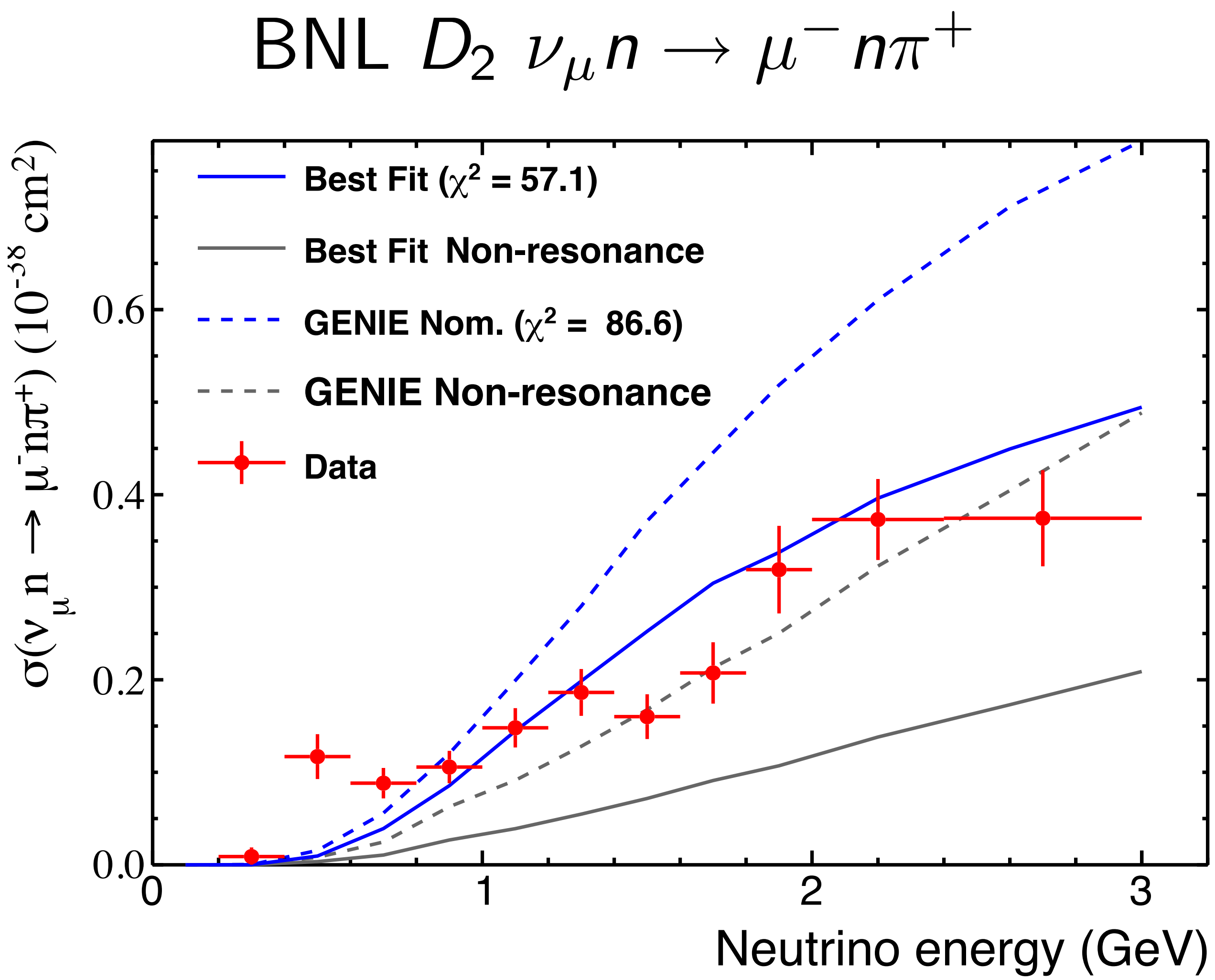
Fermilab

Simulation Updates

- MINERvA-specific tune:
  - We scale down the cross section for non-resonance pion production to match bubble chamber data
  - Include multi nucleon interactions using the Valencia model

NonResonance Pion Production

- We modify the GENIE non-resonance pion production to agree with deuterium data, Rodrigues P., Wilkinson C. & McFarland K. Eur. Phys. C (2016) 76:474



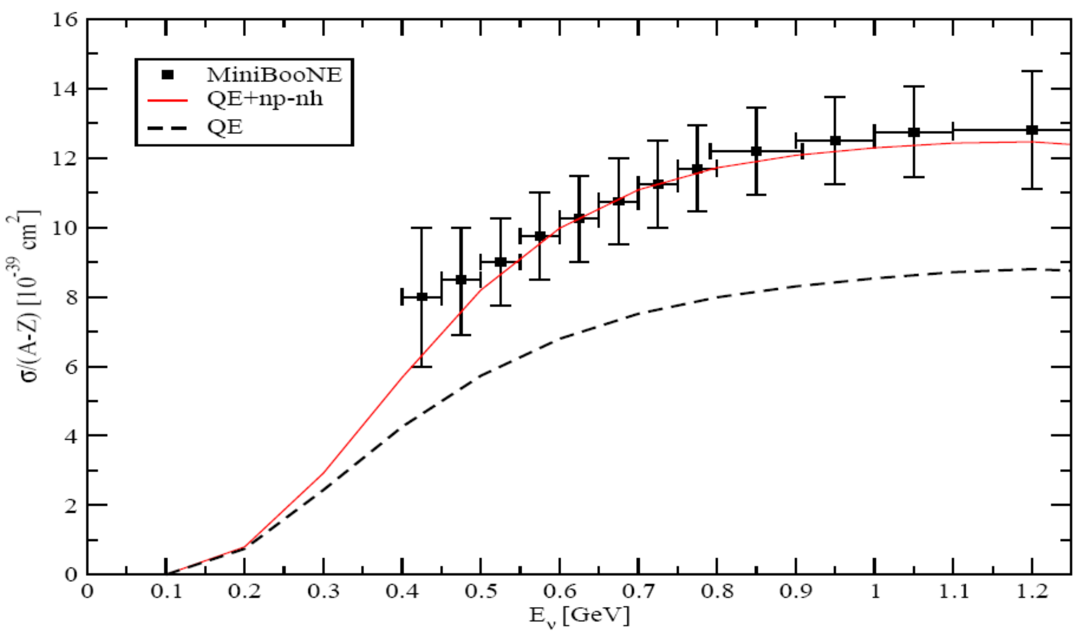
- Scale down the non-resonance pion production by 57%

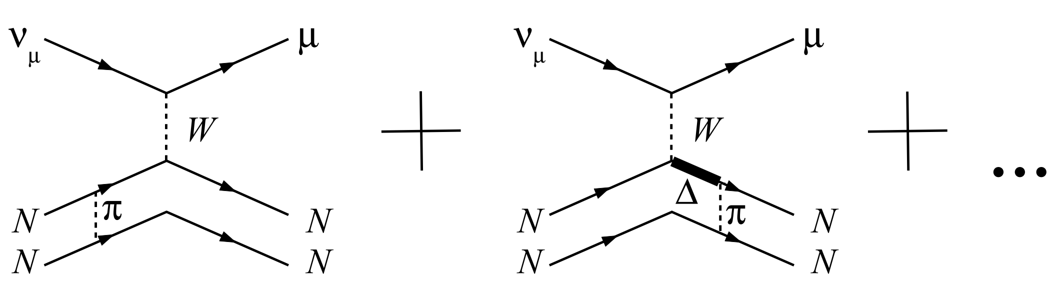
Fermilab

Including 2p2h model

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

Model compared to MiniBooNE data



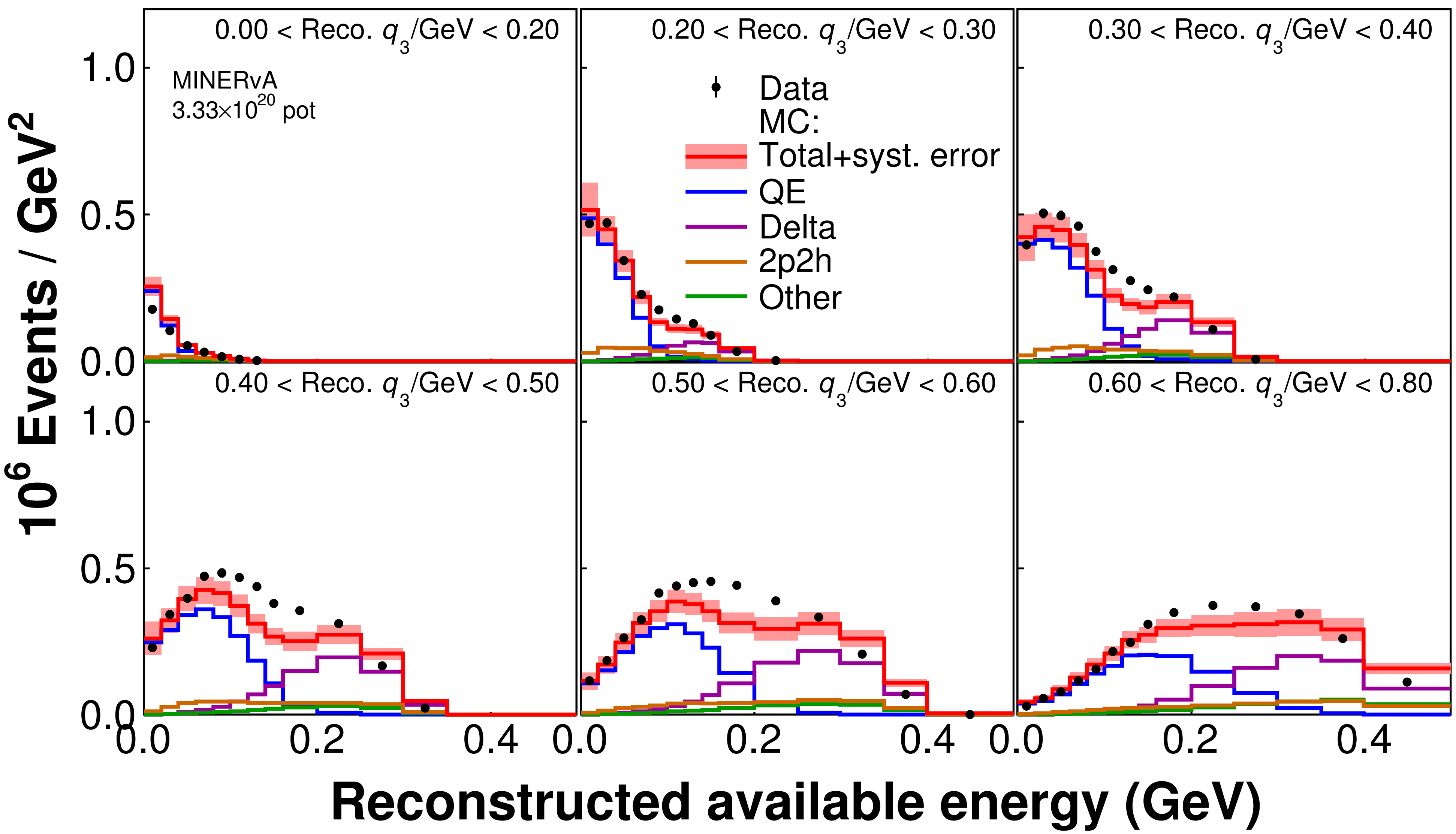


M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

- 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 2p2h model

- From a low recoil energy analysis, MINERvA found a big data excess in the region where neither 2p2h nor Delta make big contribution, even with the improvements to the model, we don't agree with data where 2p2h effects show up



Phys. Rev. Lett. 116 (2016) 071802

q3 is the three momentum transfer

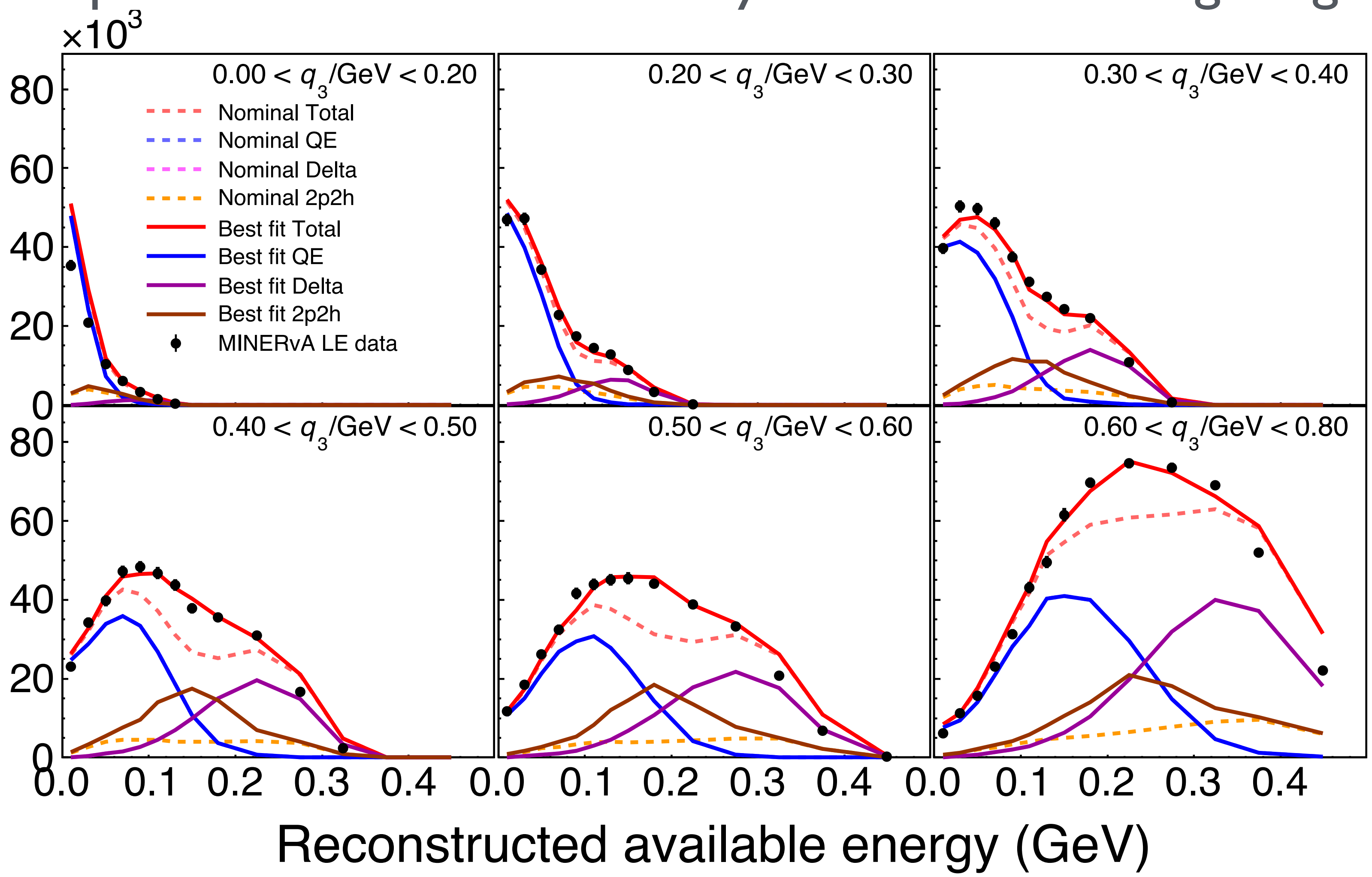
$$q_3 = \sqrt{Q^2 + \nu^2}$$

where ν is the calorimeter hadronic energy and Q² is the four momentum transfer

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

Including 2p2h model

- We use a 2d Gaussian in true variables (q_3,ν) as a reweighting function applied to the 2p2h events, and fits its parameters to get the best agreement between data and MC (QE and RES are unchanged)
- We will include 2p2h in the MC for our analysis with this reweighting

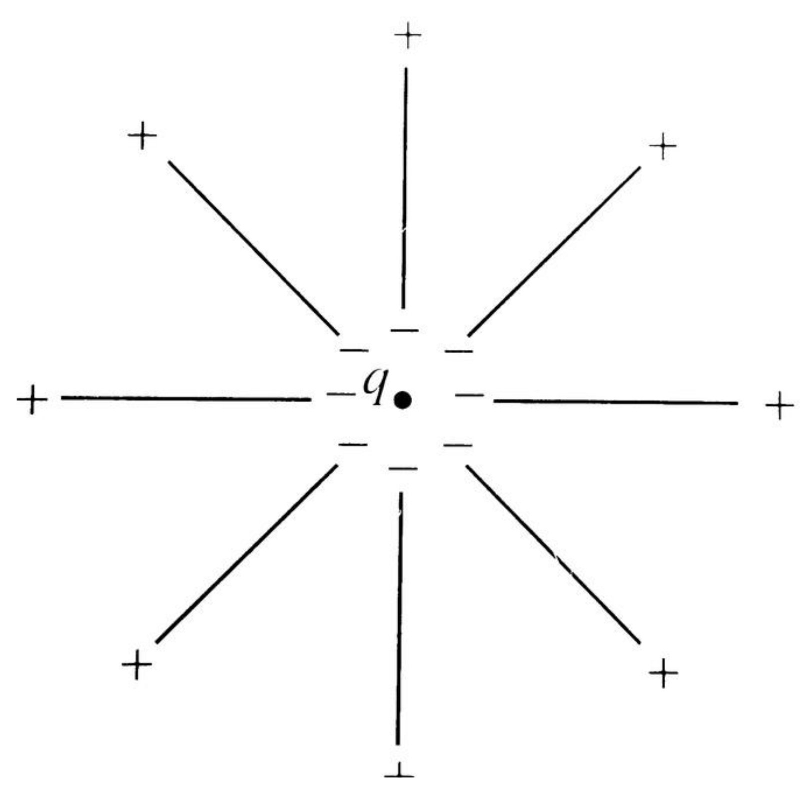


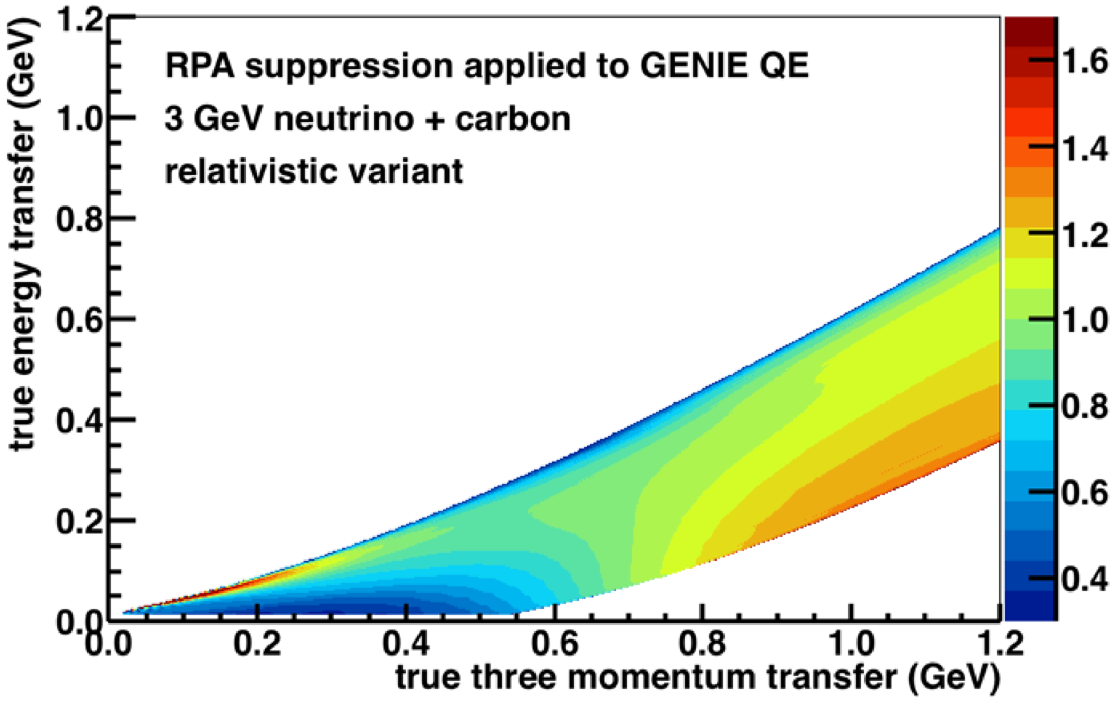
- 2p2h events can involve an initial-state nn or np pair. For a systematic, we take extreme cases of only reweighting events on an nn pair, and only reweighting events on an np pair. We can again apply these weights to the CCQE analysis

Fermilab

Including Random Phase Approximation (RPA)

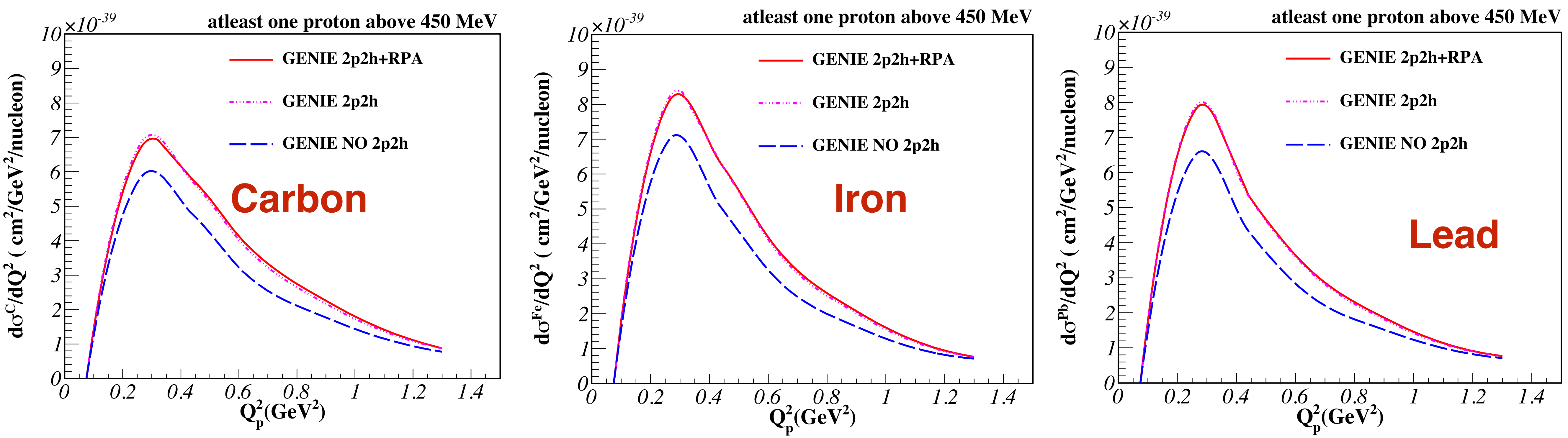
- Analogous to screening of electric charge in a dielectric
- For neutrino scattering in a nucleus, imagine the W as having a weak charge and polarizing the nuclear medium
- Calculated using Random phase approximation (RPA), PRC 70, 055503 (2004)
- We add the RPA to GENIE by reweighting the QE events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





Effect of 2p2h and RPA

- Comparisons of differential cross sections with different simulations no 2p2h, 2p2h, and 2p2h+RPA

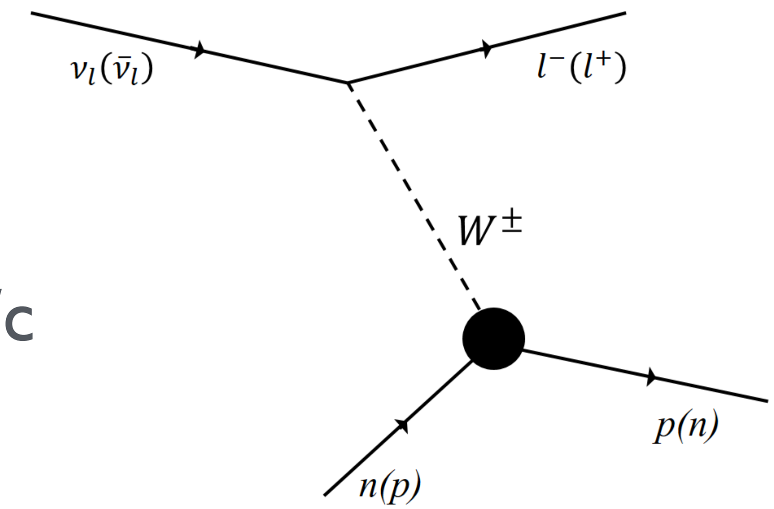


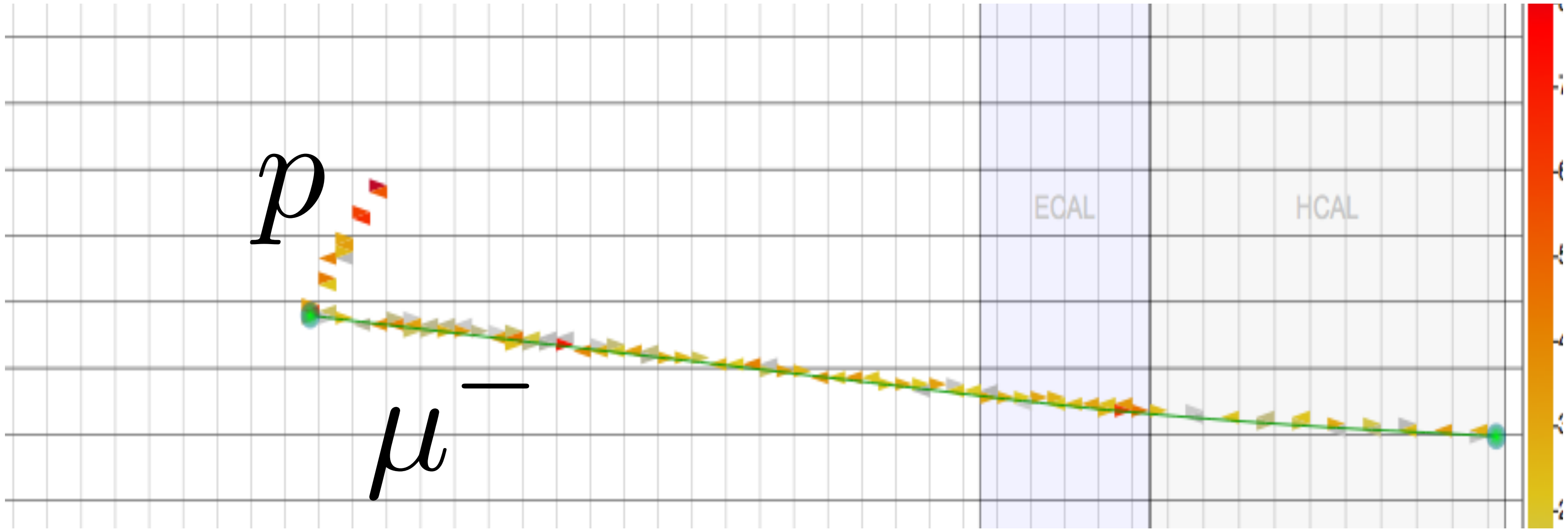
- There is an A dependence in the 2p2h model
- Most of the RPA suppression is below the proton threshold 450 MeV

Analysis

Signal (CCQE-Like)

- Signal:
  - One muon
  - No pions
  - At least one proton with momentum >450 MeV/c





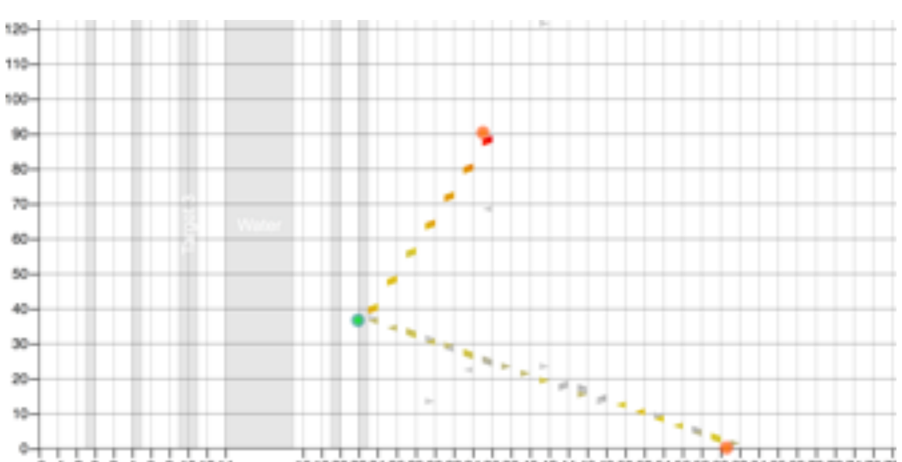
Event Selection Overview

- At least two tracks
- Reconstructed vertex is in the target material
- Proton particle identification score: remove events with pions
- Michel electron cut: remove events with low-energy pions by searching for Michel electron

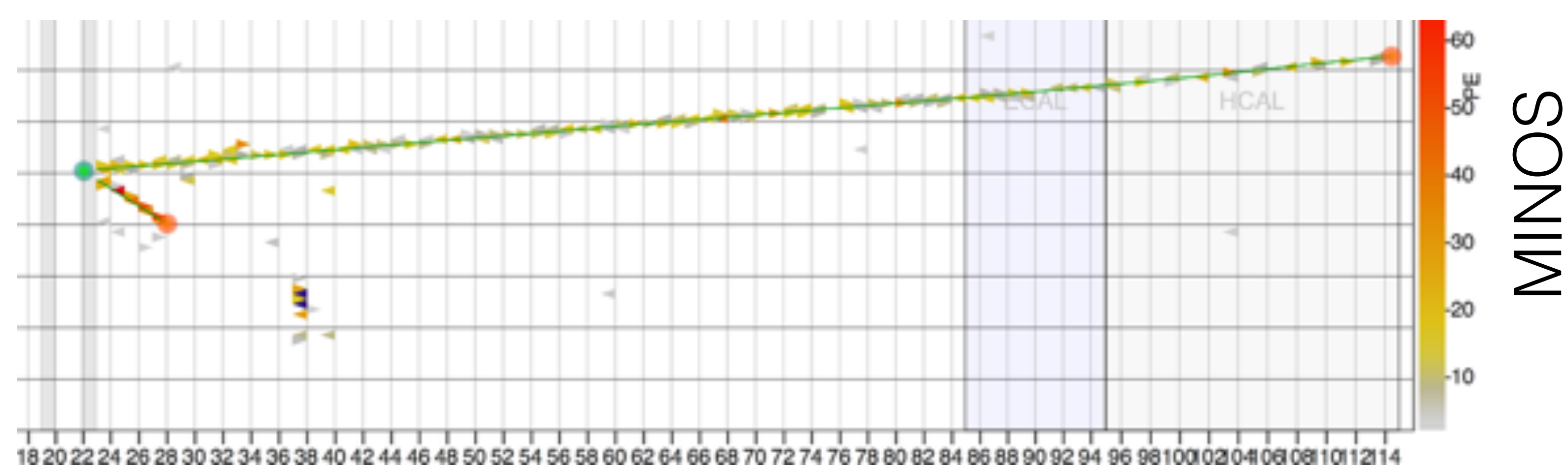
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu} \\ \mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu} \end{array}$$

- Cut on energy far from the vertex: remove inelastic events with untracked pion

Analysis includes events with muons that exit the sides of MINERvA



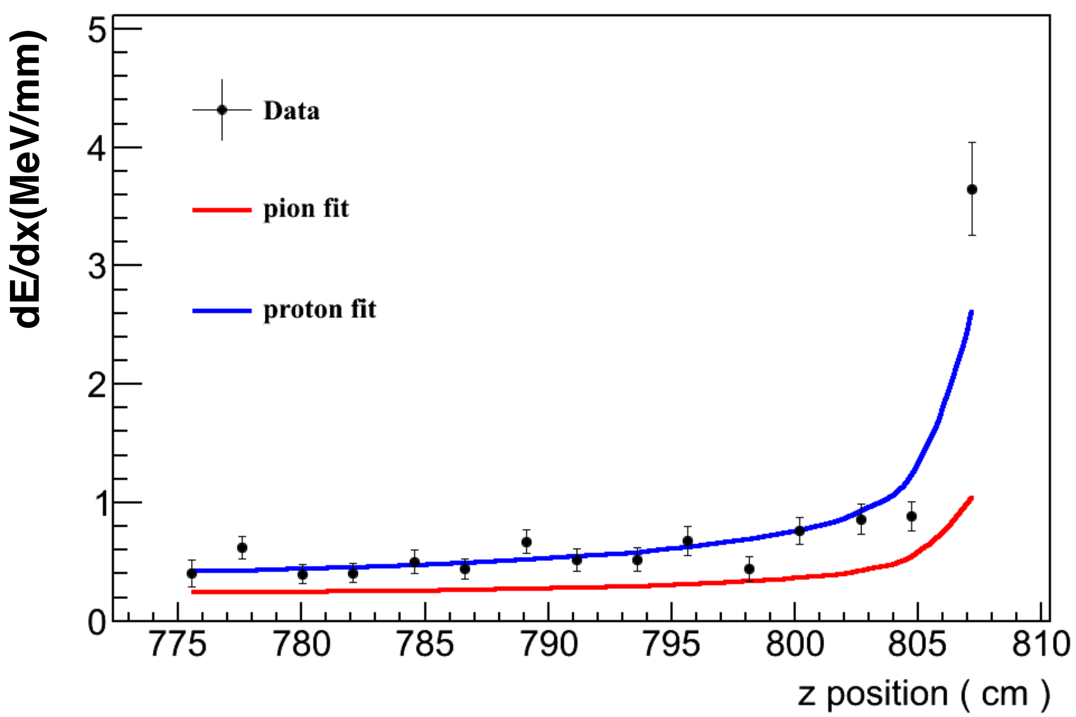
Analysis includes events with muons matched to MINOS



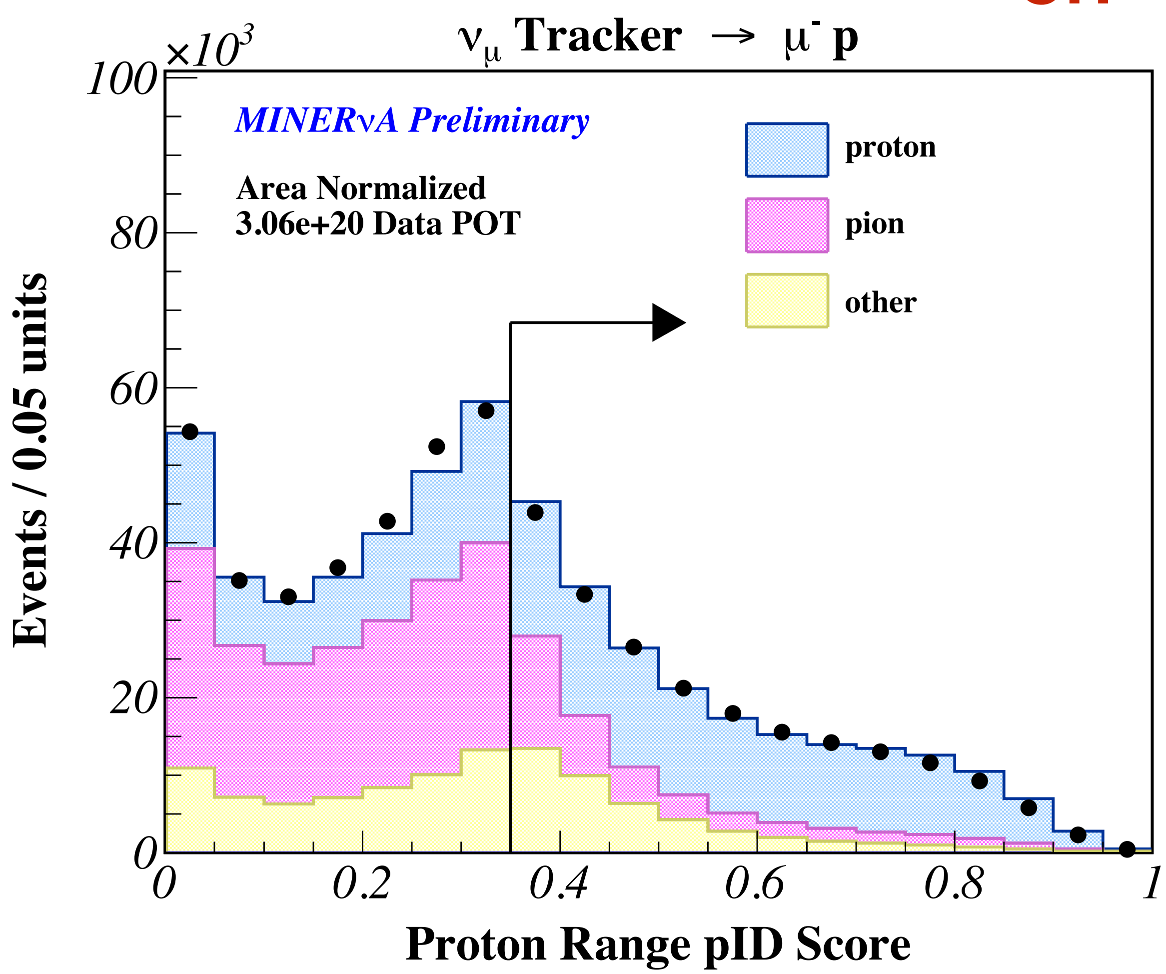
Fermilab

Selecting Events with Protons (Proton pID Score Cut)

- Require events with a proton candidate
  - Fit each hadron track energy loss dE/dx profile to both pion and proton loss profile for particle identification
  - Use the χ^2/dof values from pion and proton fits to create a score and select the proton candidate

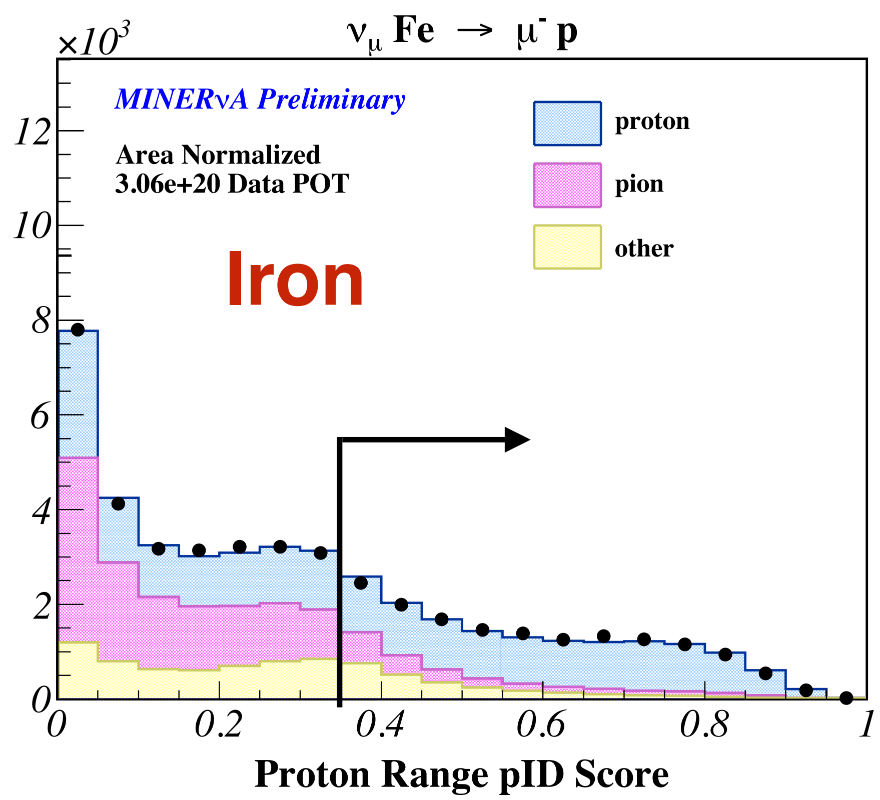


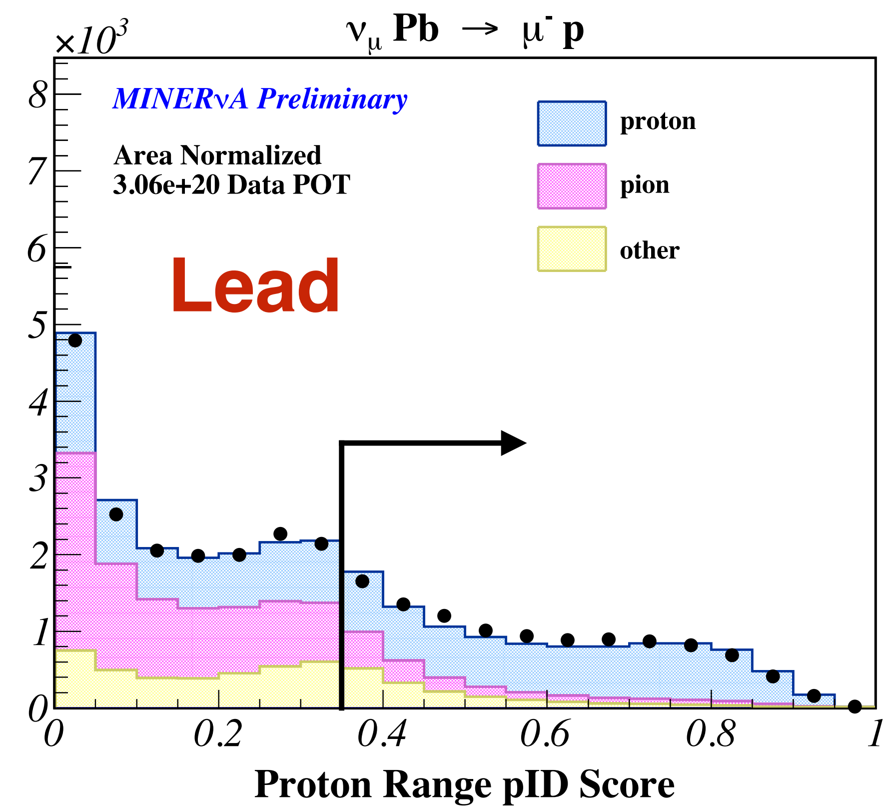
CH



Selecting Events with Protons

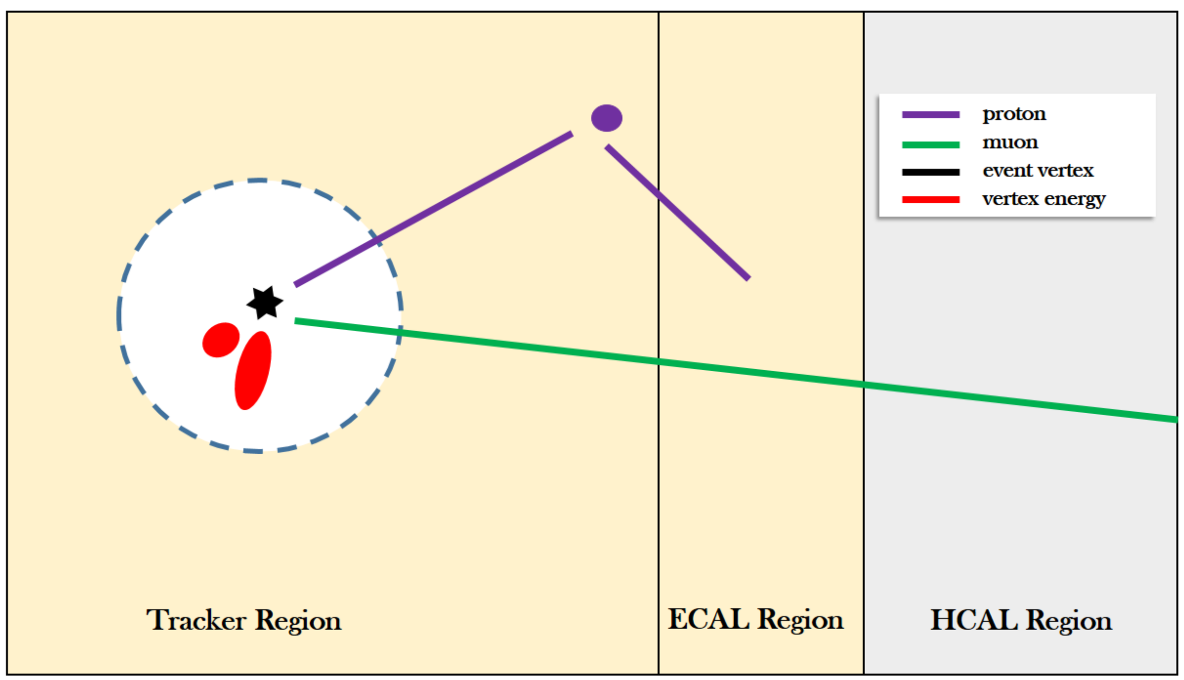
- Require events with a proton candidate
  - Fit each hadron track energy loss, dE/dx profile to both pion and proton loss profile for particle identification
  - Use the χ^2/dof values from pion and proton fits to create a score and select the proton candidate



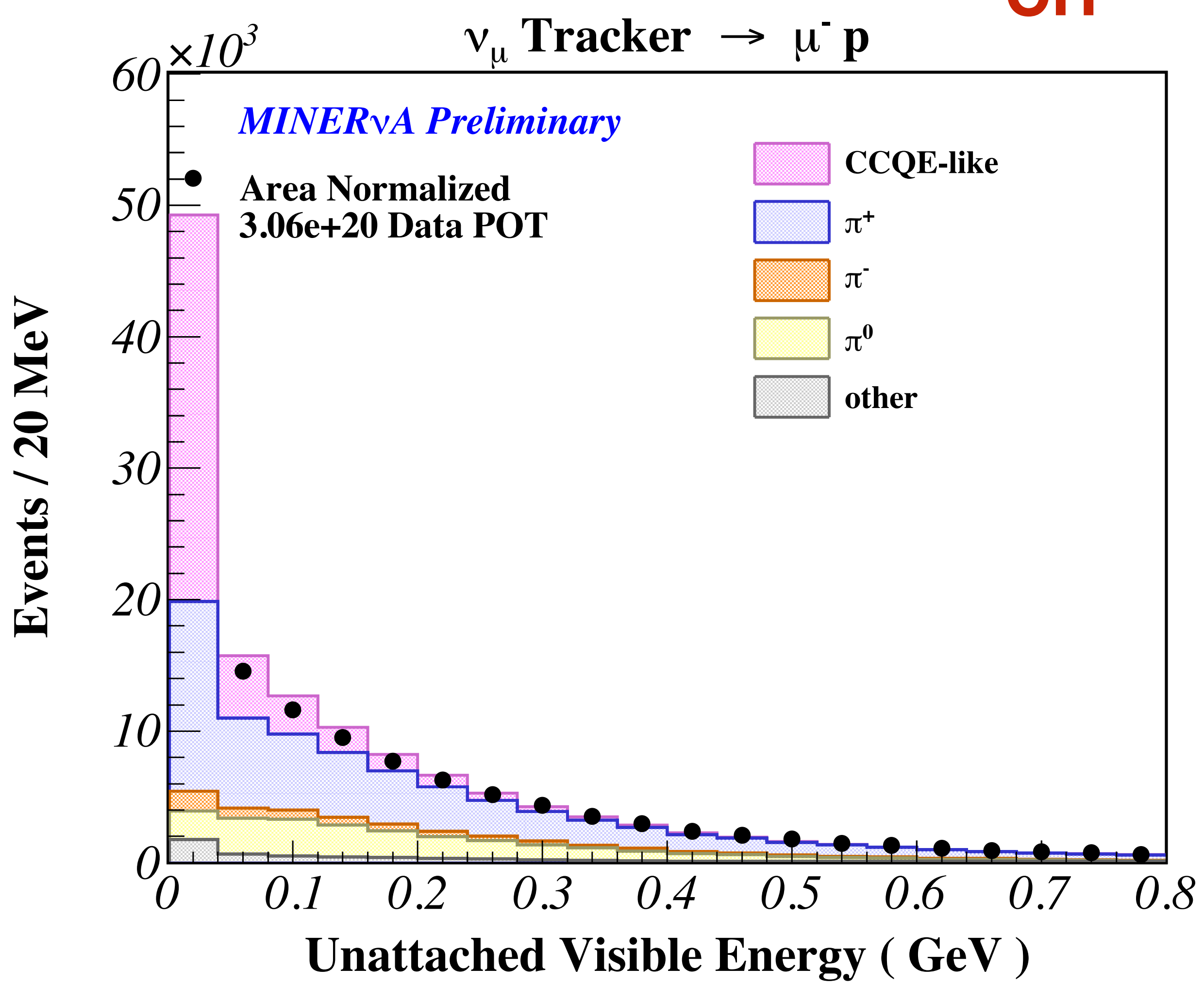


Removing Background Events Safely

- We define a variable called unattached visible energy, which is the sum of the visible energy that is outside of the sphere (radius=10cm)



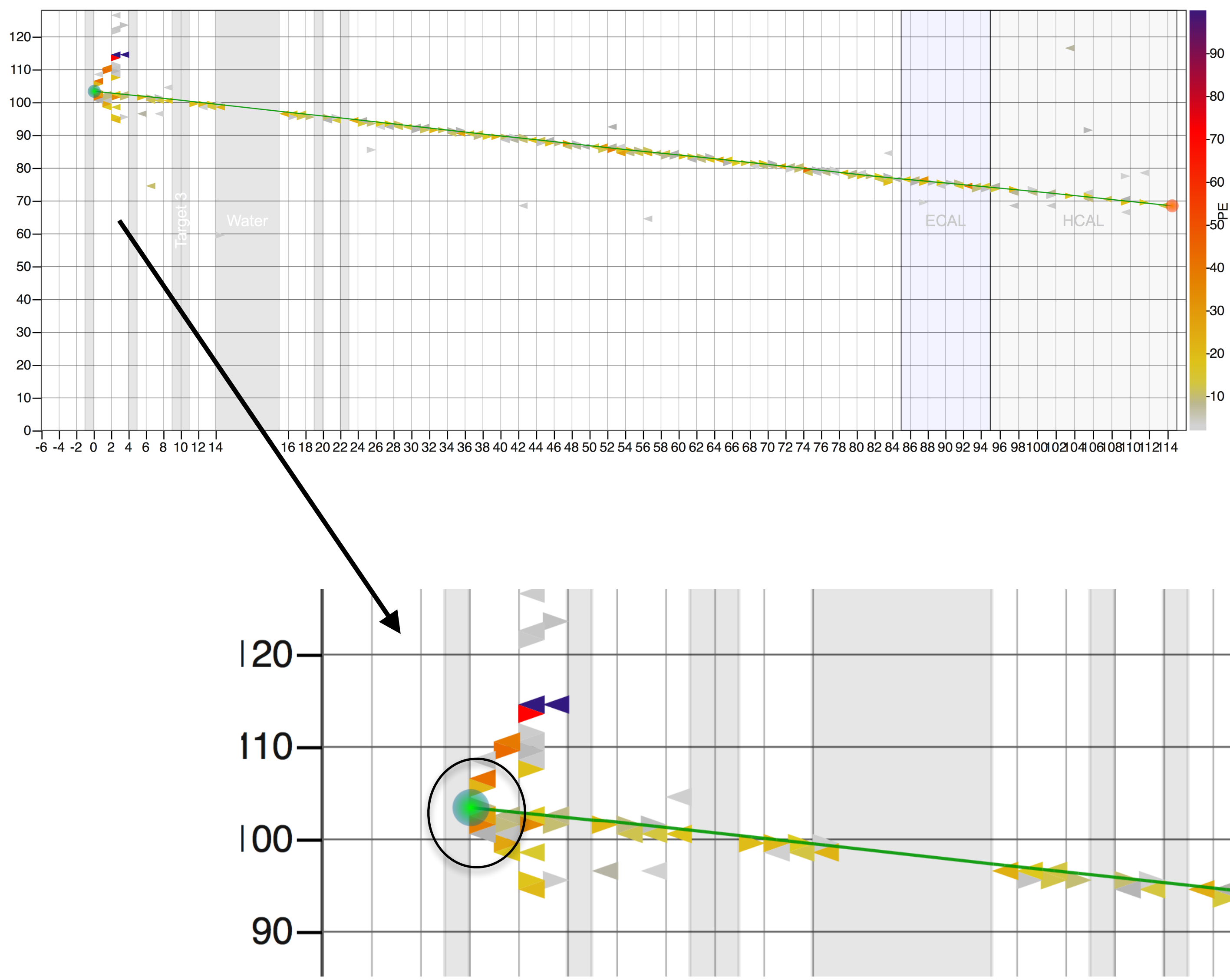
CH

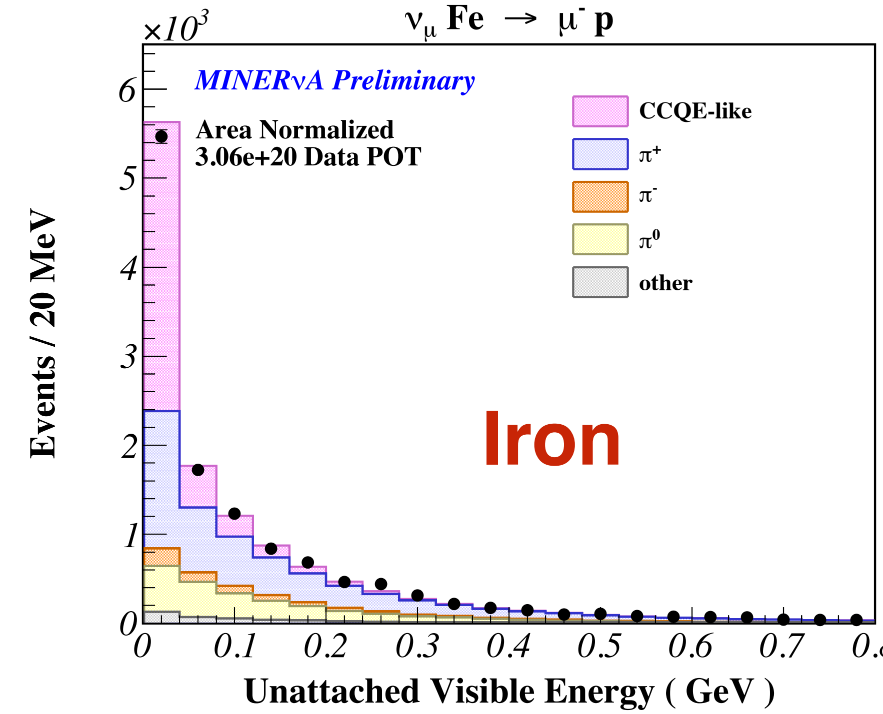


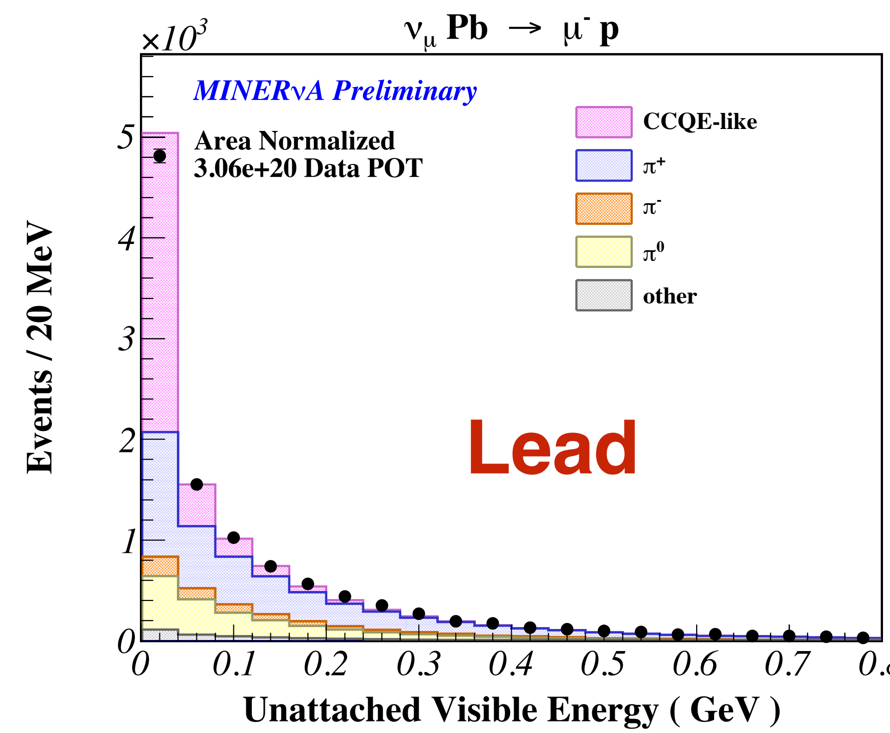
Fermilab

Removing Background Events

- We define a variable called unattached visible energy, which is the sum of the visible energy that is outside of the sphere (radius=10cm)



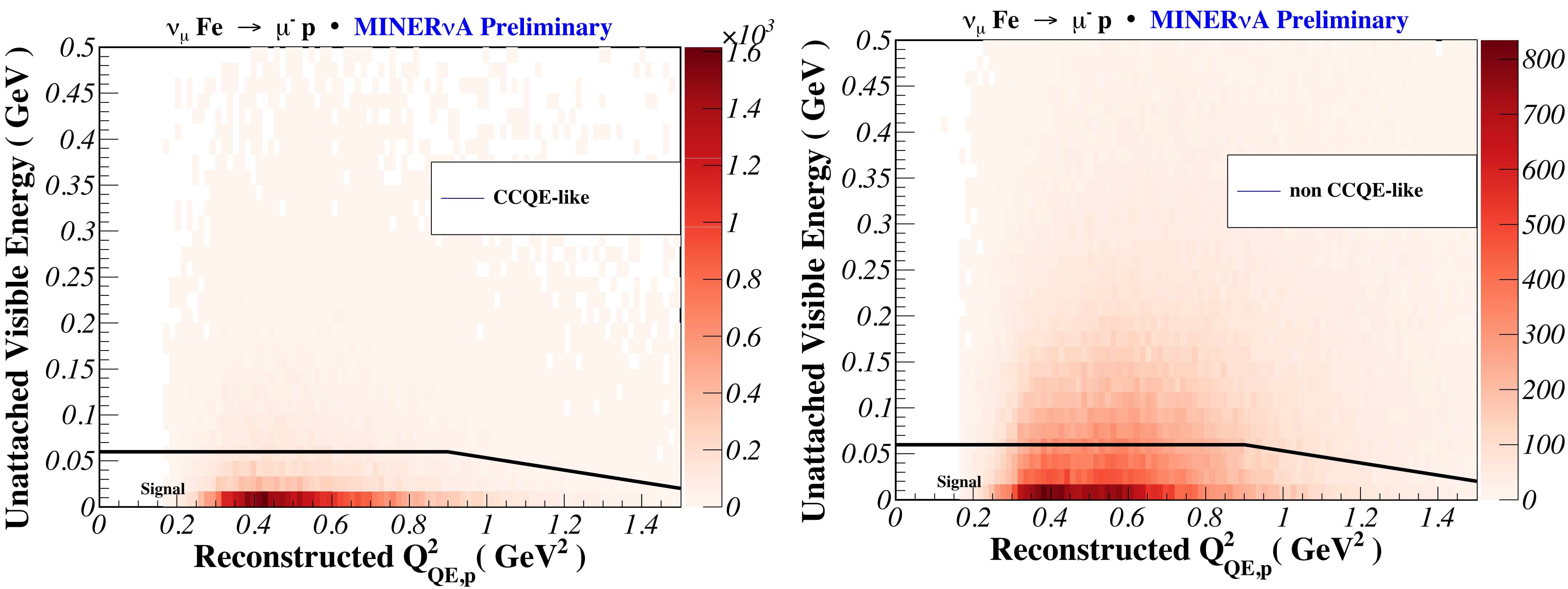




Unattached Visible Energy vs Q^2 Cut

- The unattached visible energy is used to reject background events
- Distributions for signal and background events

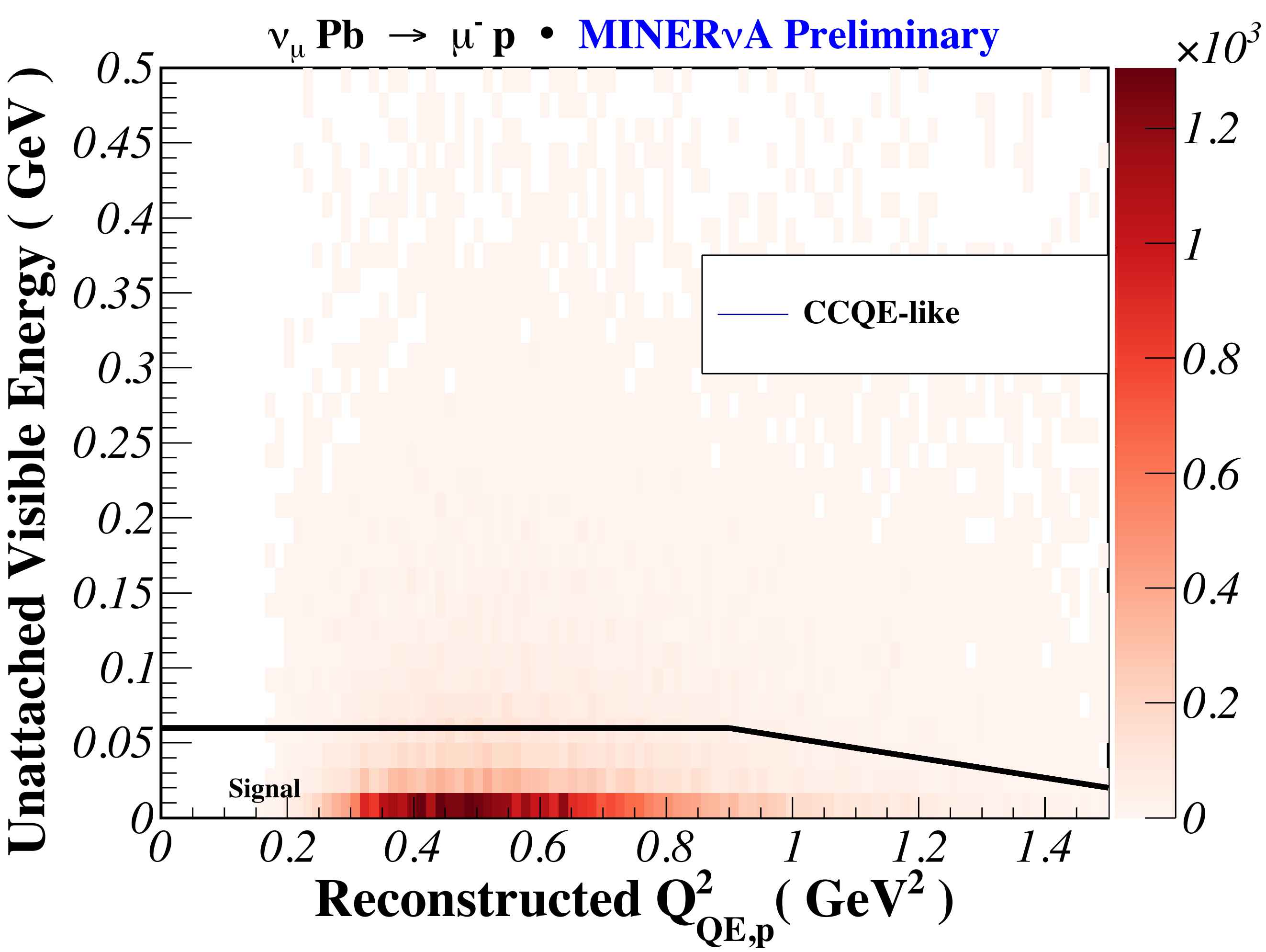
Iron

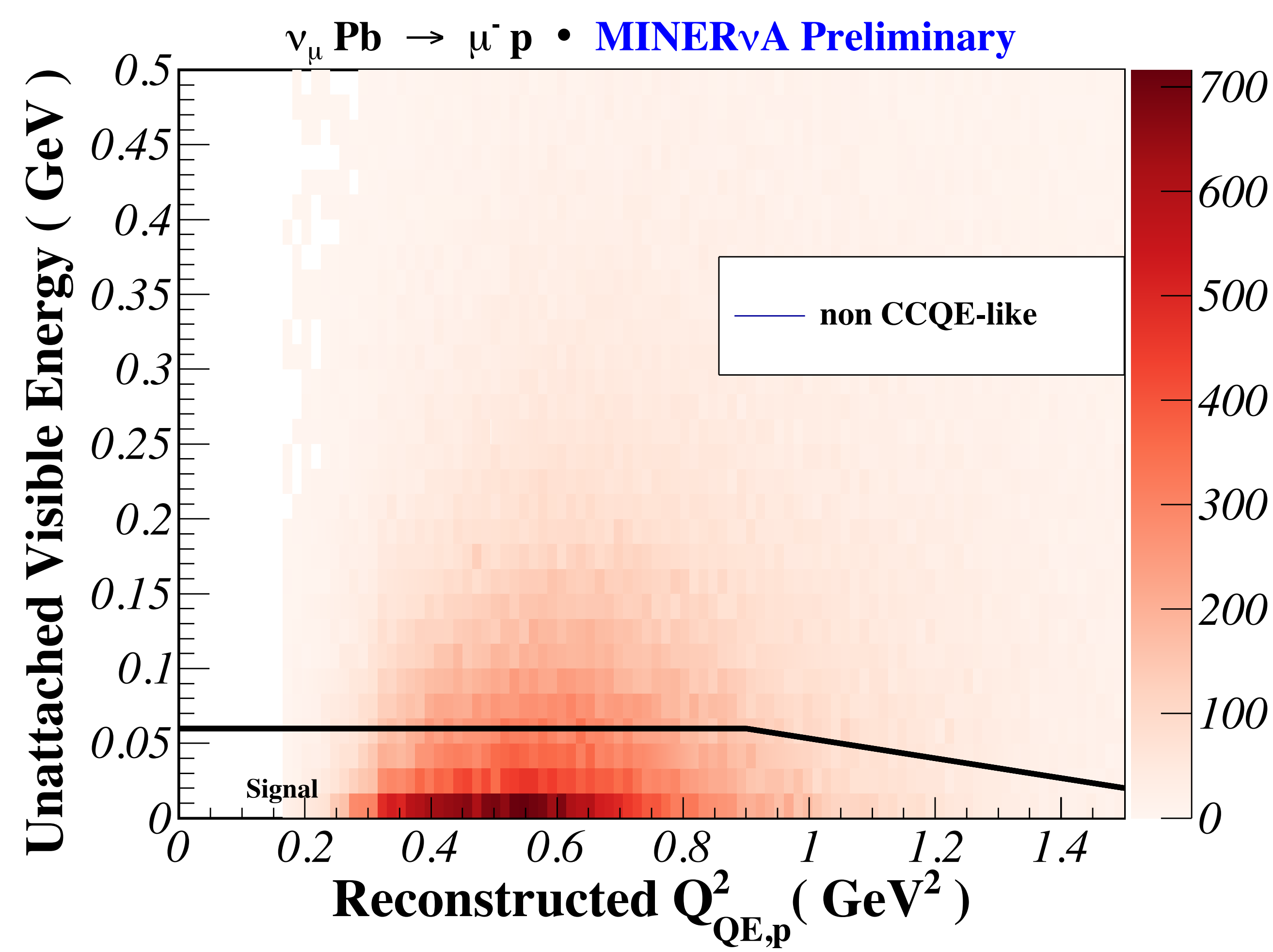


Unattached Visible Energy vs Q^2 Cut

- The unattached visible energy is used to reject background events
- Distributions for signal and background events

Lead

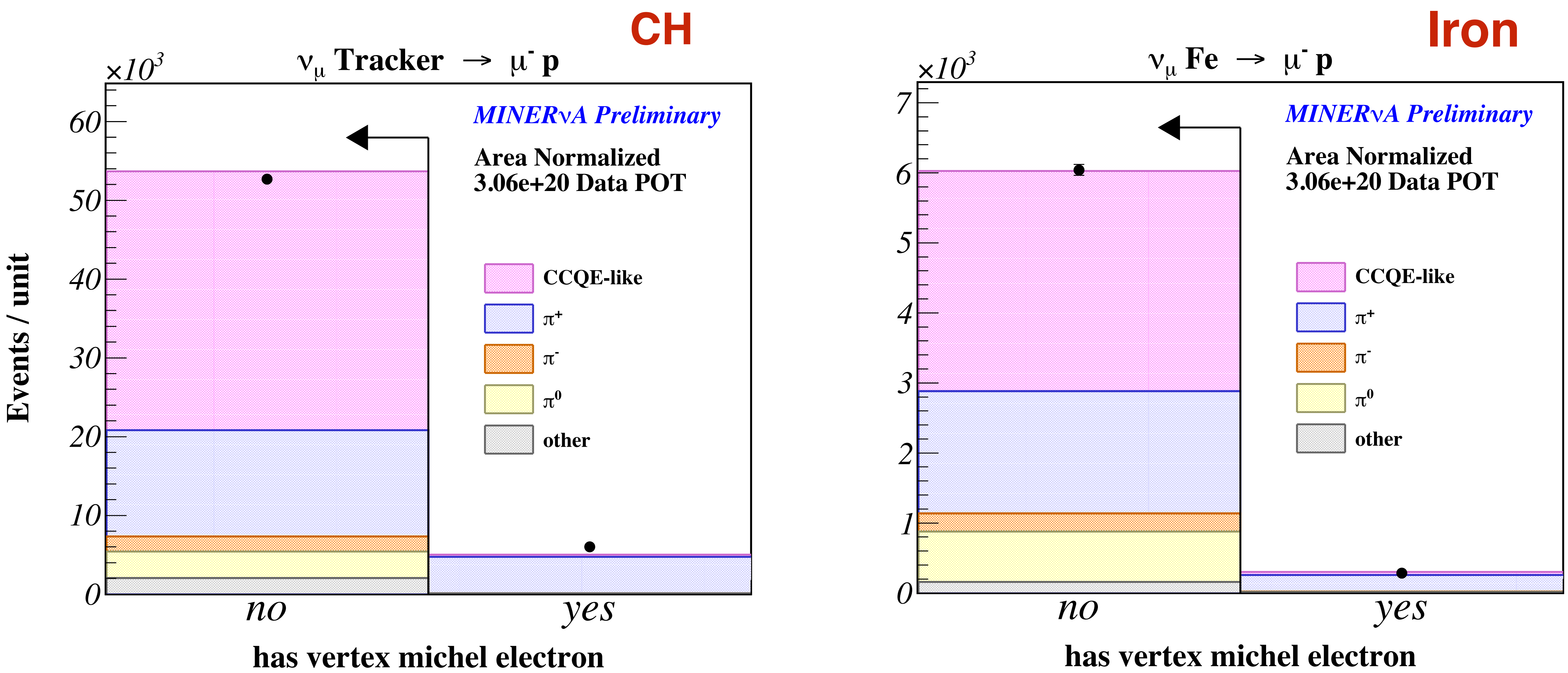




Michel Veto

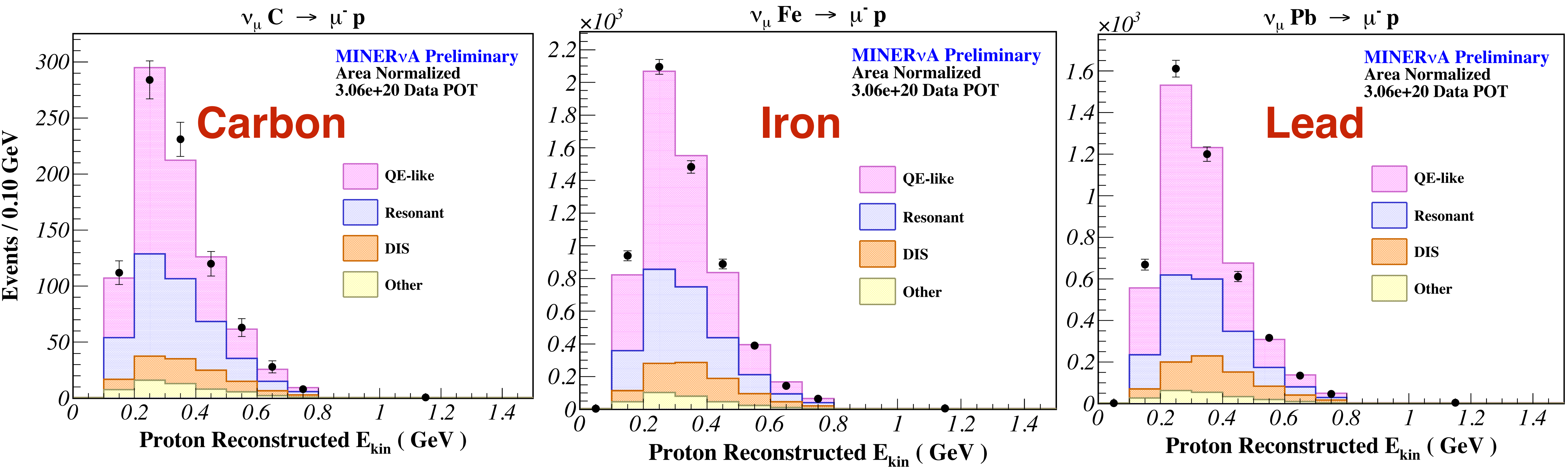
- Removing events with a Michel electron found near the interaction vertex

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^{-} \to e^{-}\bar{\nu_e}\nu_{\mu} \\ \mu^{+} \to e^{+}\nu_e\bar{\nu_{\mu}} \end{array}$$



Selected Sample

- Events passing the analysis selection cuts

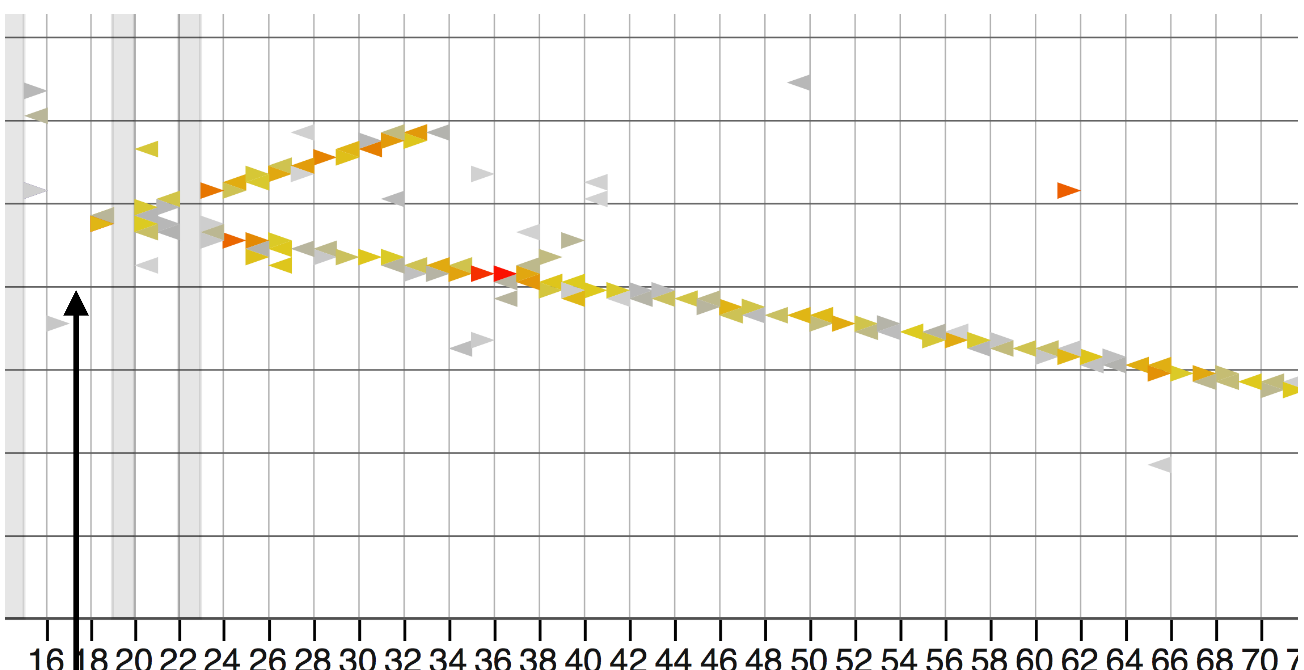


- The dominant background is from resonance events
  - Resonance background events ~30%, deep inelastic background events 10%

Background Constraint Procedure

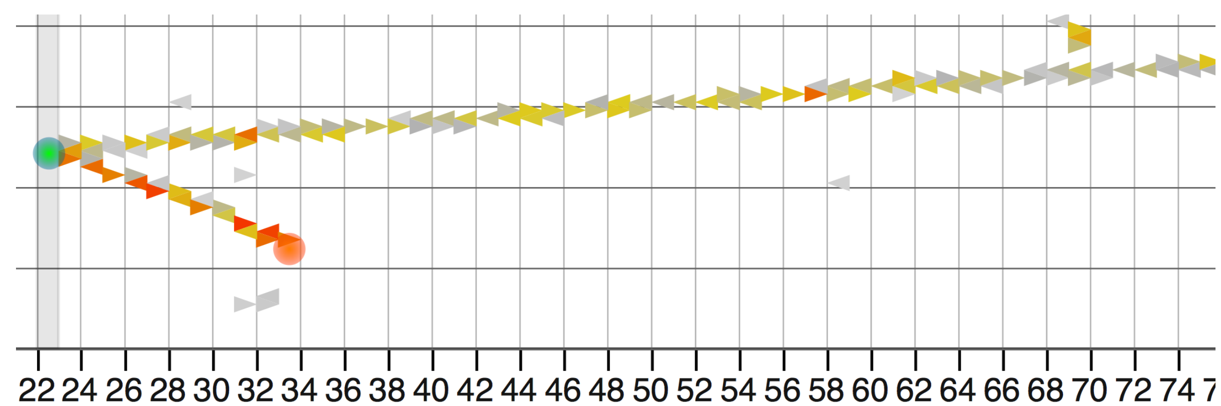
- Backgrounds:
    1. Scintillator background: events that occurred outside the nuclear targets
    2. Non-CCQE like background: where the pions have been misidentified as proton, not remove by cuts

Scintillator background



Interaction outside the target

Non-CCQE Background

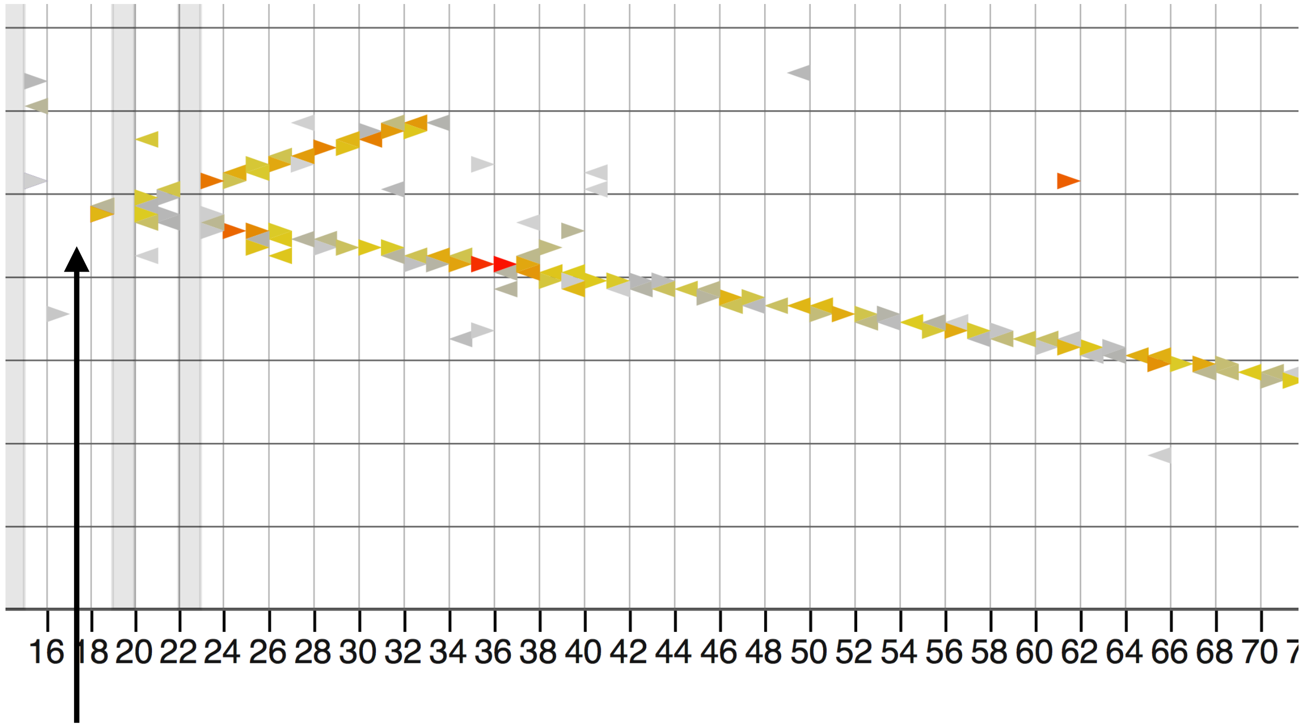


DIS interaction

Scintillator Background

- Scintillator background: events that occurred outside the nuclear targets

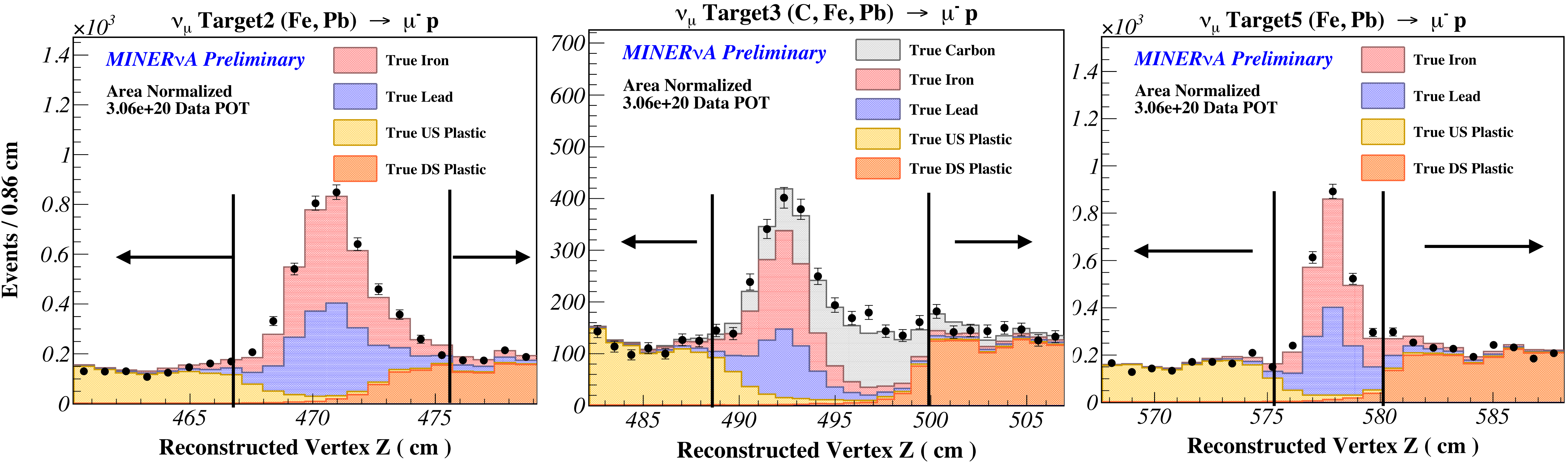
Scintillator background



Interaction outside the target

Sidebands to Constrain the Scintillator Background

- Removing the z cut, tails of the distributions are scintillator dominated events
- Regions outside the fiducial volume are used to constrain the scintillator background
- We fit the tails of the distributions for each target separately and extract a scale factor for the scintillator background

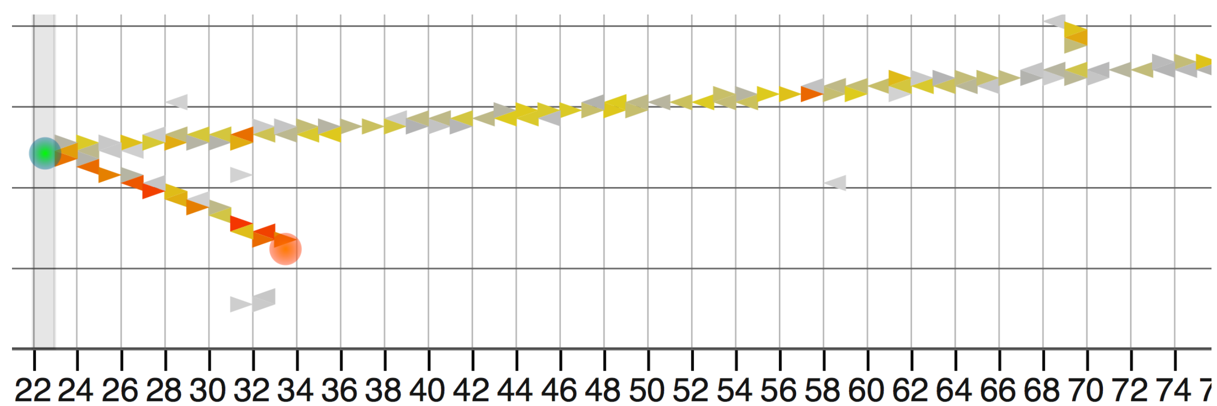


- Different scintillator scale factor for each target: Target 2 (0.99), Target 3 (0.90), Target 5 (1.1)

Non-CCQE like Background

- Pions have been misidentified as proton, not remove by cuts

Non-CCQE Background



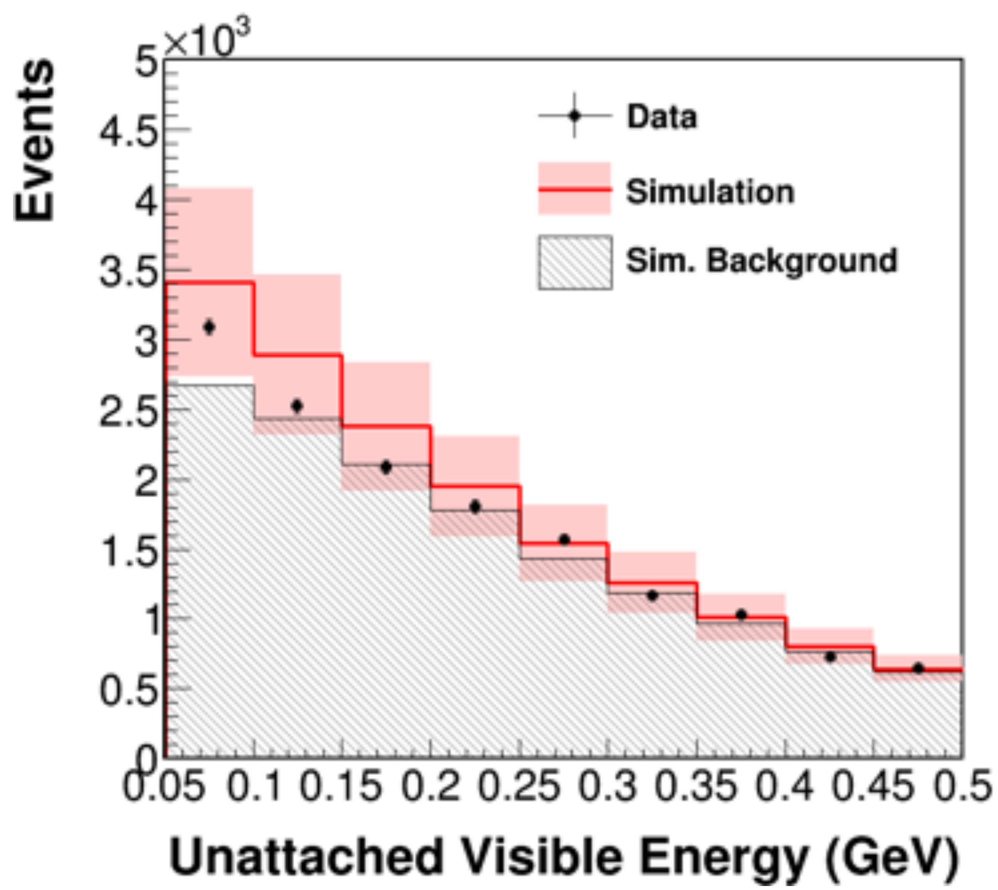
DIS interaction

Background Constraint Procedure for Non-CCQE like

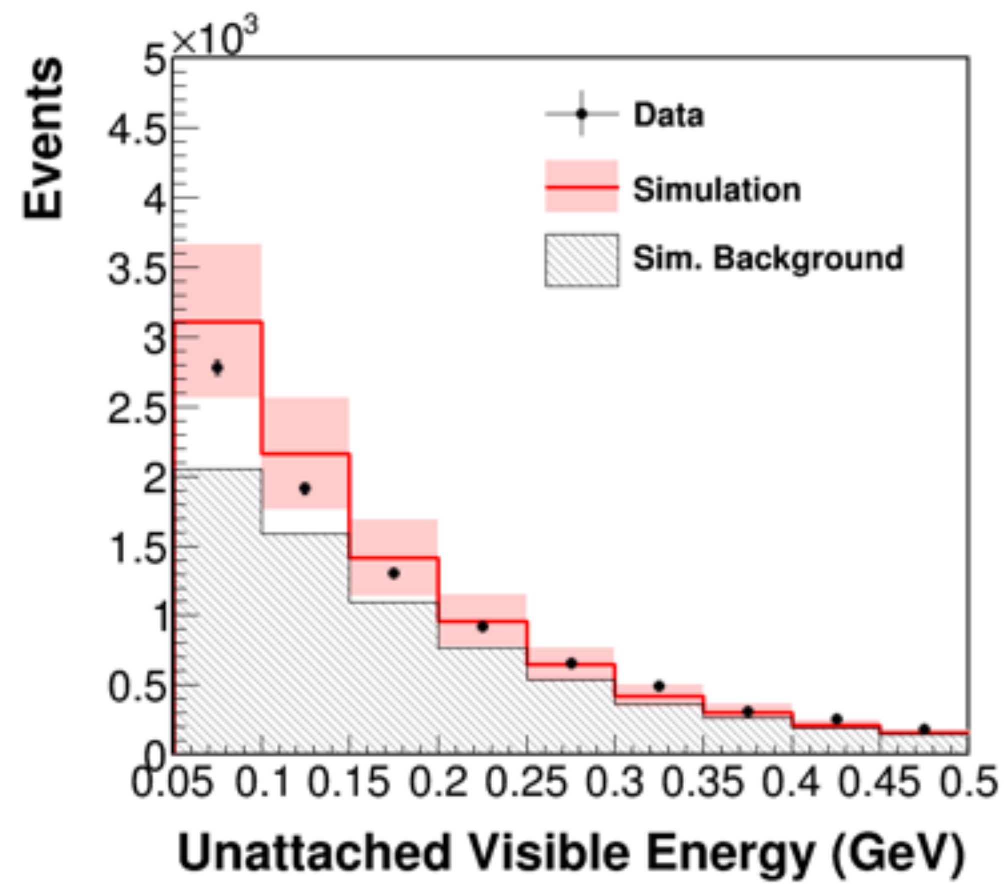
- Using the unattached visible energy for the events passing the proton pID for two different bins of Q^2 in the tracker
- Using the background dominated region in the unattached visible energy distribution
- Let the background float in the fit while keeping the signal constant until the total matches the data distributions

Before the constraint

Q^2<0.5GeV^2



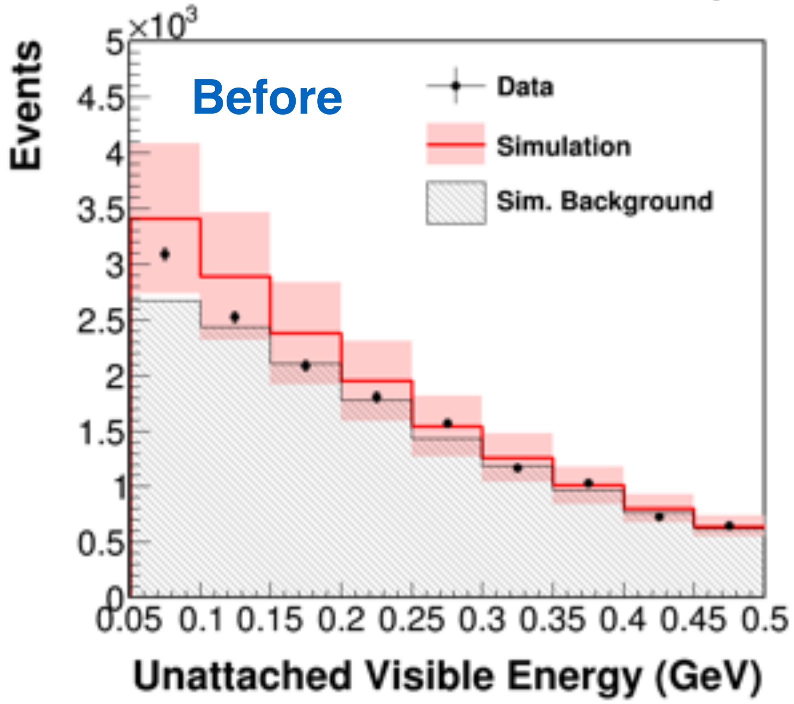
Q^2>0.5GeV^2

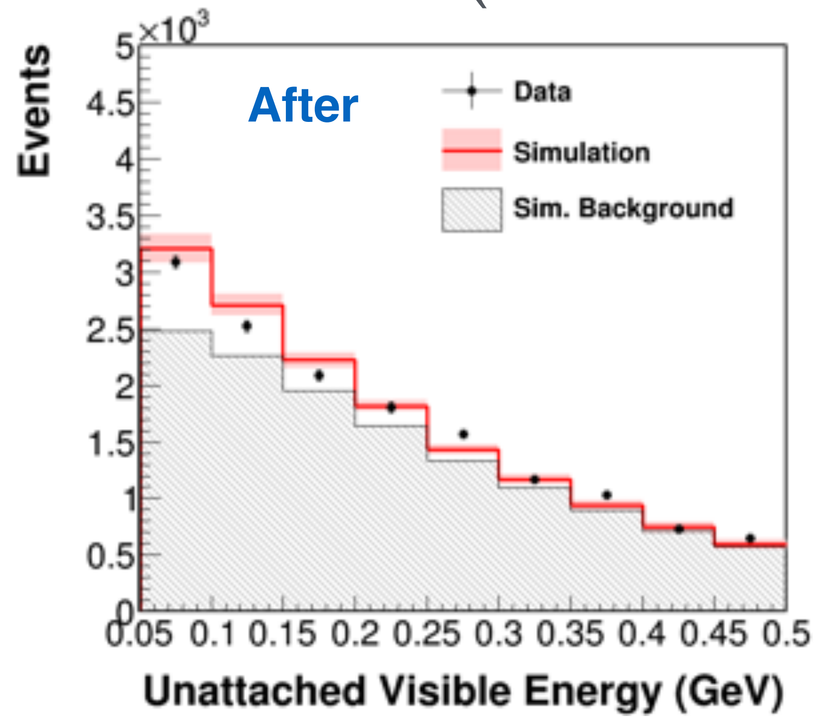


First Method

- Signal is fixed in the fit, background scale factor (0.93+/-0.01)

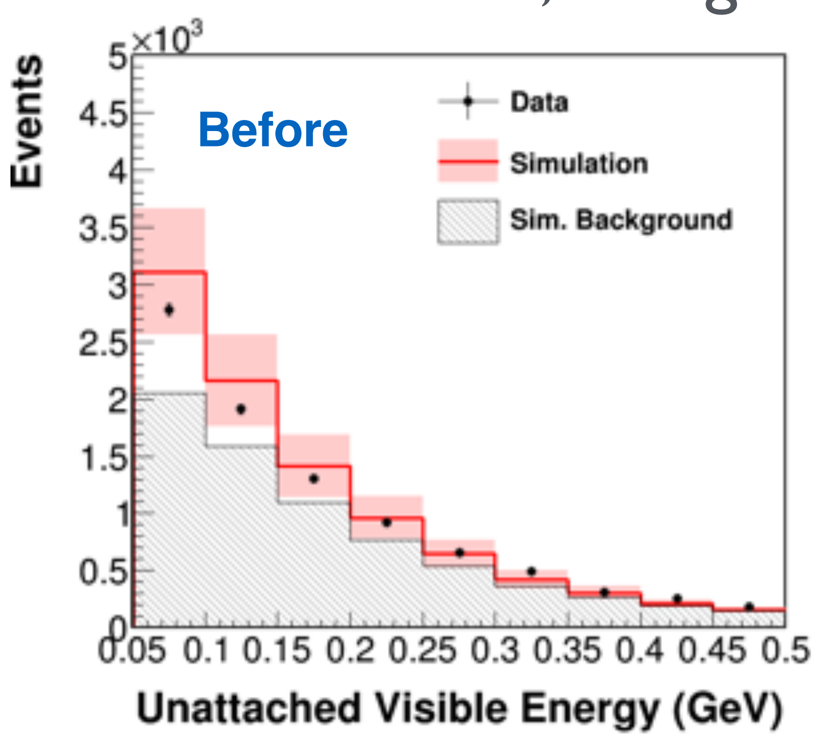
Q^2<0.5GeV^2

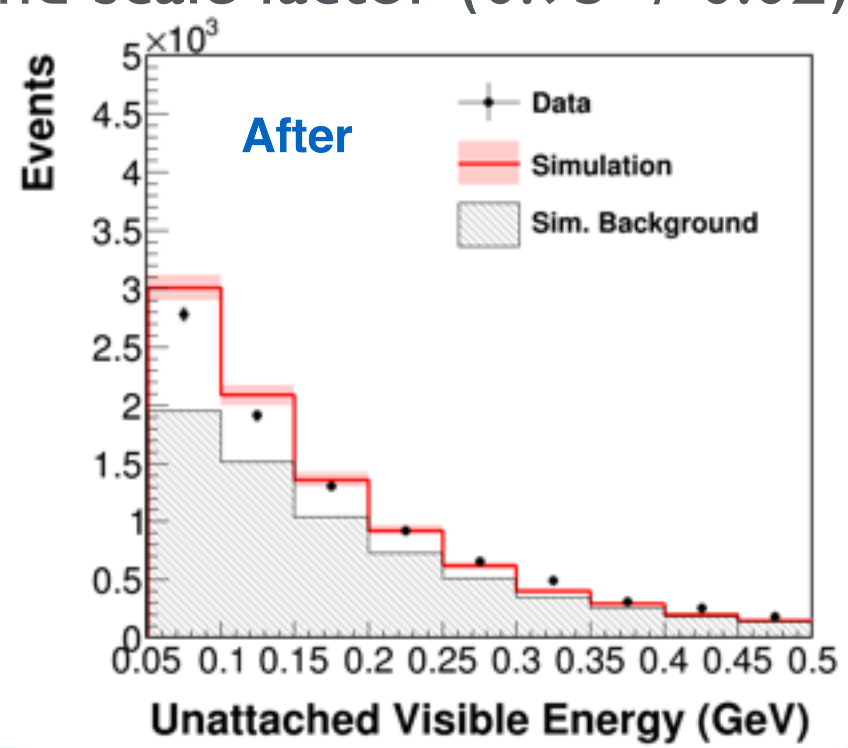




- Signal is fixed in the fit, background scale factor (0.95+/-0.02)

Q^2>0.5GeV^2



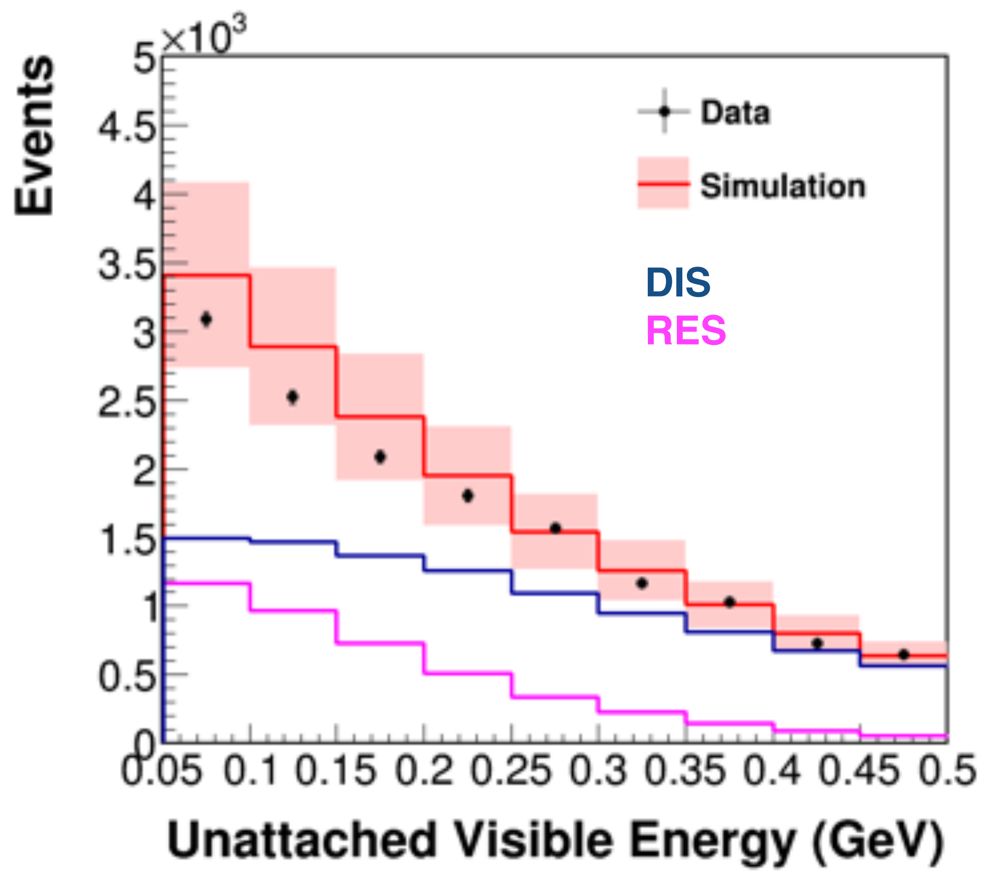


Second Method

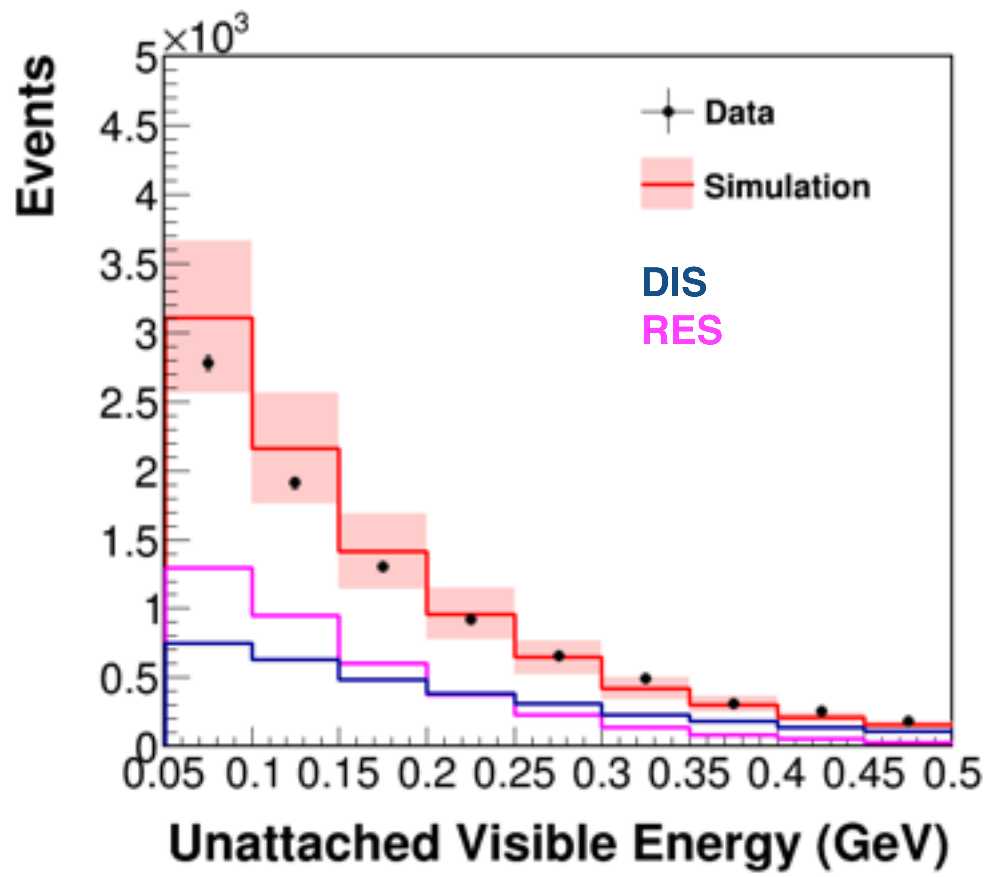
- Separating the background components into RES and DIS, letting the fit float the background components and keeping the signal fixed

Before the constraint

$Q^2 < 0.5 GeV^2$



$Q^2 > 0.5 GeV^2$

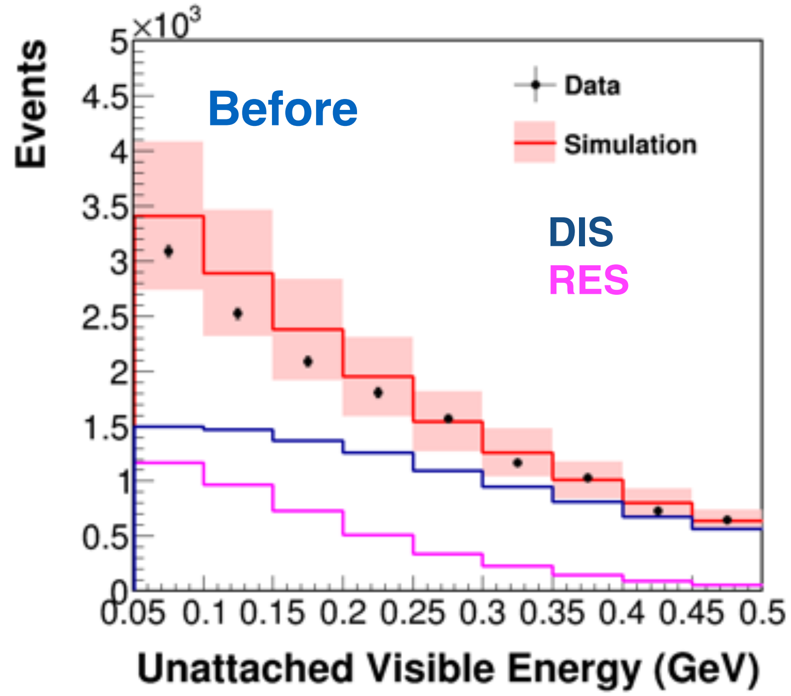


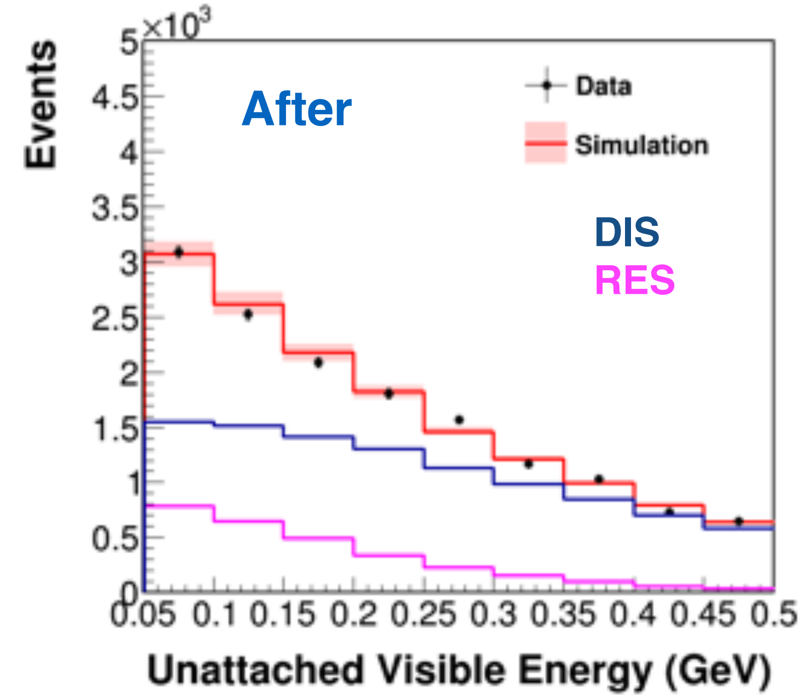
Fermilab

Second Method Separate the Backgrounds into his Components

- Letting the fit float the background components and keeping the signal fixed; RES=0.67+/-0.08 and DIS=1.03+/-0.03

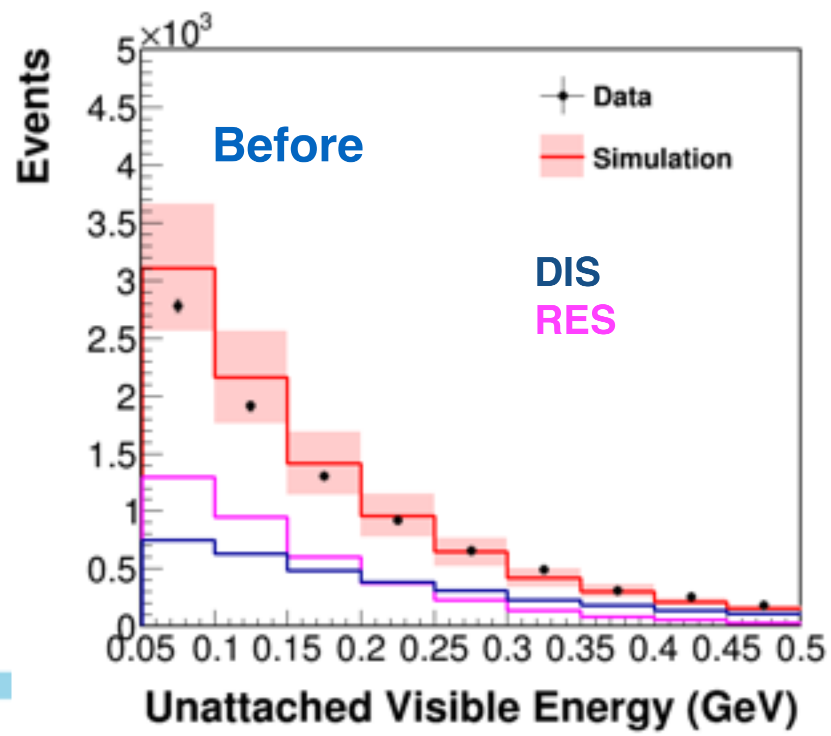
$Q^2 < 0.5 GeV^2$

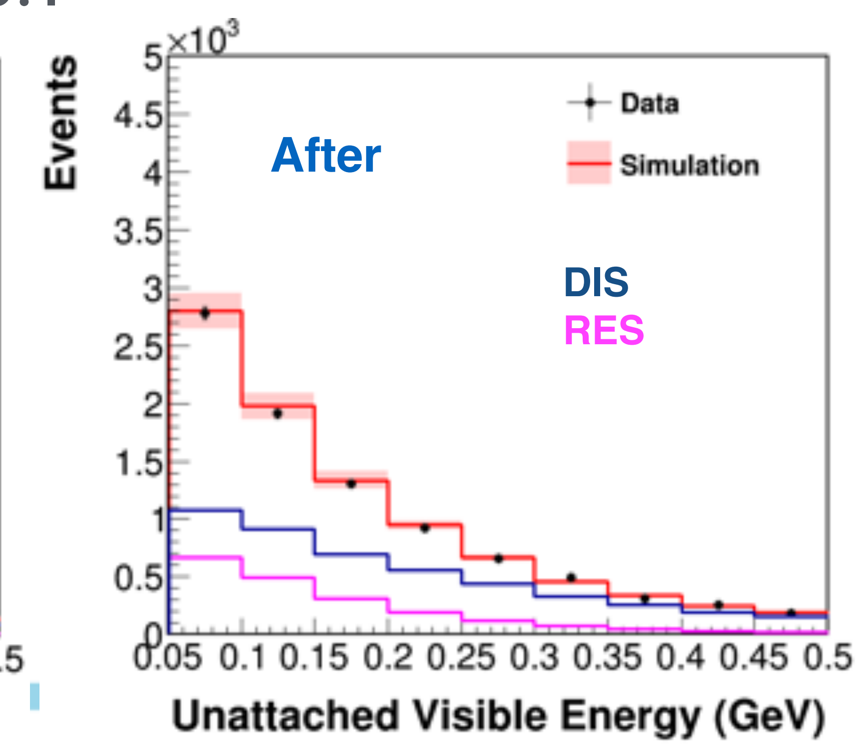




- RES=0.5+/-0.09 and DIS=1.4+/-0.1

$Q^2 > 0.5 GeV^2$





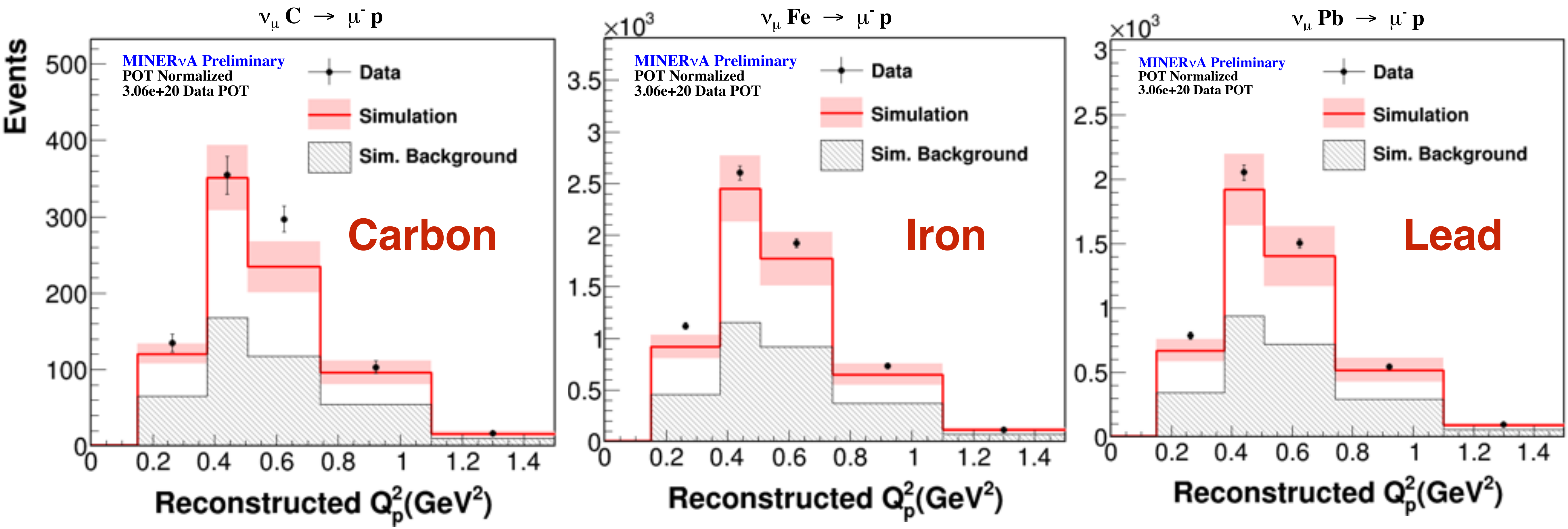
Fermilab

Background Constraint Procedure

- For the tracker, the predicted background from both methods differ by ~10%
- In the nuclear targets we have less information in the unattached visible energy distribution and much fewer statistics compared with data from the tracker region
- The two component fit is not as stable for iron, lead and carbon for some regions of Q^2 as for the tracker, due to similar shapes in the resonance and deep inelastic scattering distributions
- We use the one component fit in the analysis and assign an extra systematic uncertainty (10%) to account for the difference between the procedures

Reconstructed Proton Q^2

- After all the cuts

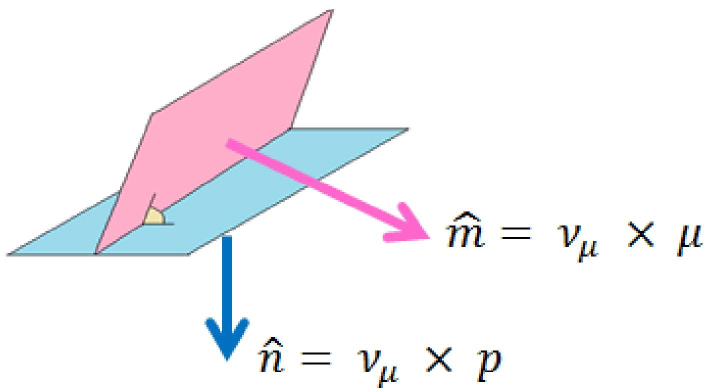


- Background has been tuned
- Distributions contain the background from the scintillator

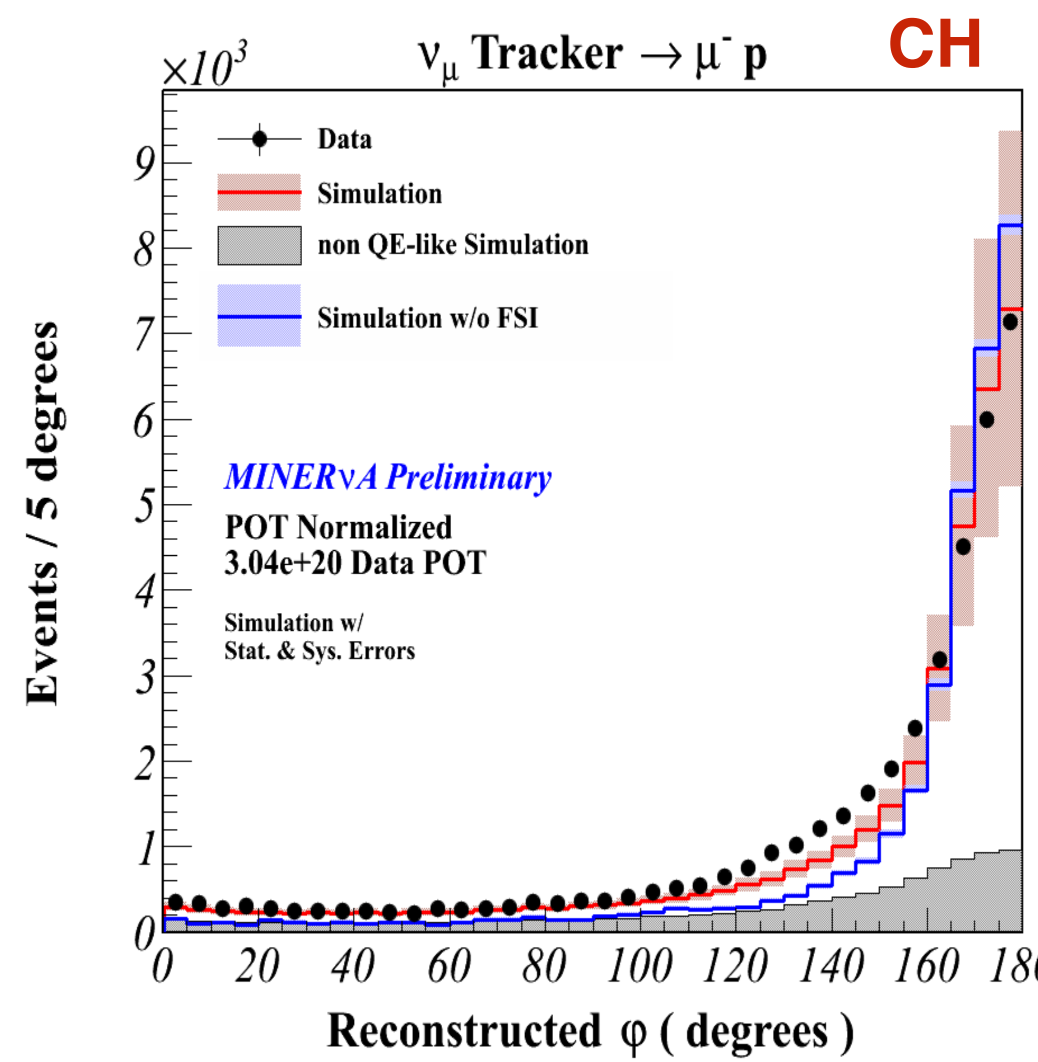
Fermilab

Coplanarity Angle

- Protons are very sensitive to final state interactions
- A clear effect of final state interactions can be shown with the coplanarity angle, which is the angle between the ν-muon and ν-proton plane



$$\varphi = \cos^{-1}\left(\frac{(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu)\cdot(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p)}{|\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu||\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p|}\right)$$

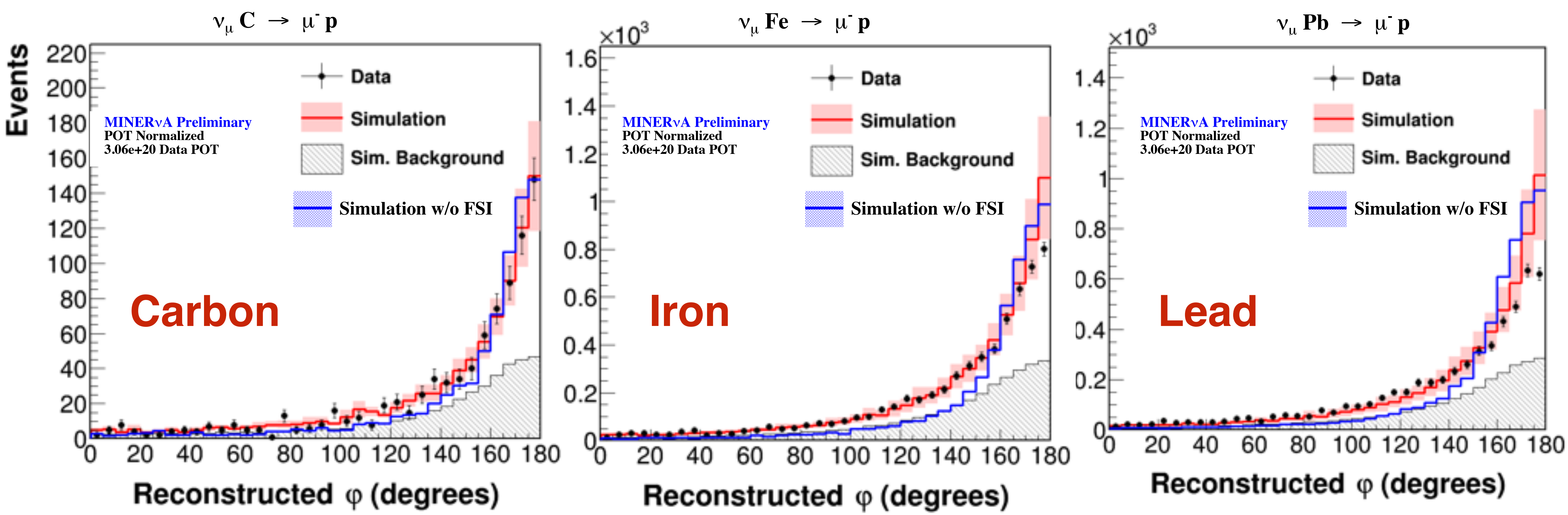


Phys. Rev. D. 91, 071301 (2015)

- Detector resolution on φ is 3.8 degrees, the width is due to Fermi motion, inelastic scattering and FSI effects

Coplanarity Angle

- After all the cuts



- Background has been tuned
- Data/MC discrepancy increases with A

Measuring Differential Cross Section

- Standard equation to measure the differential cross section

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

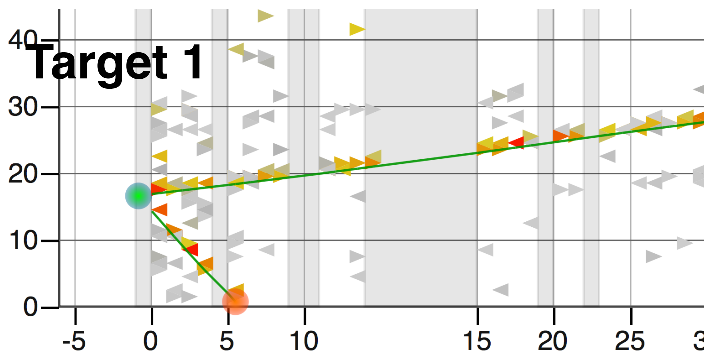
Efficiency

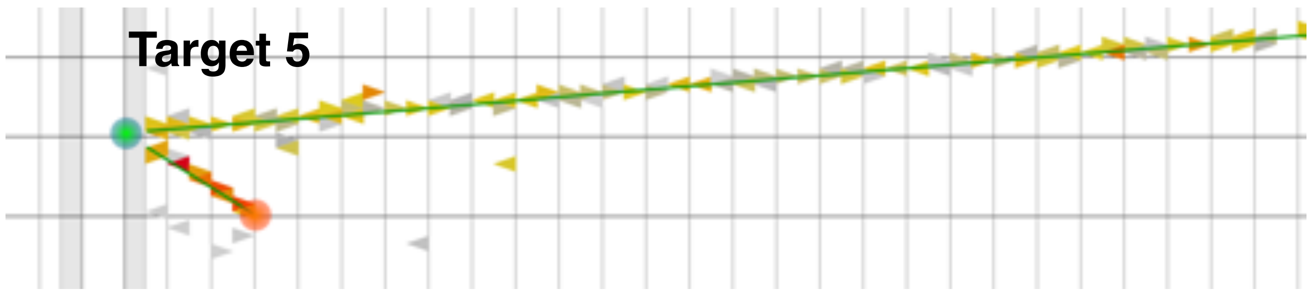
Flux

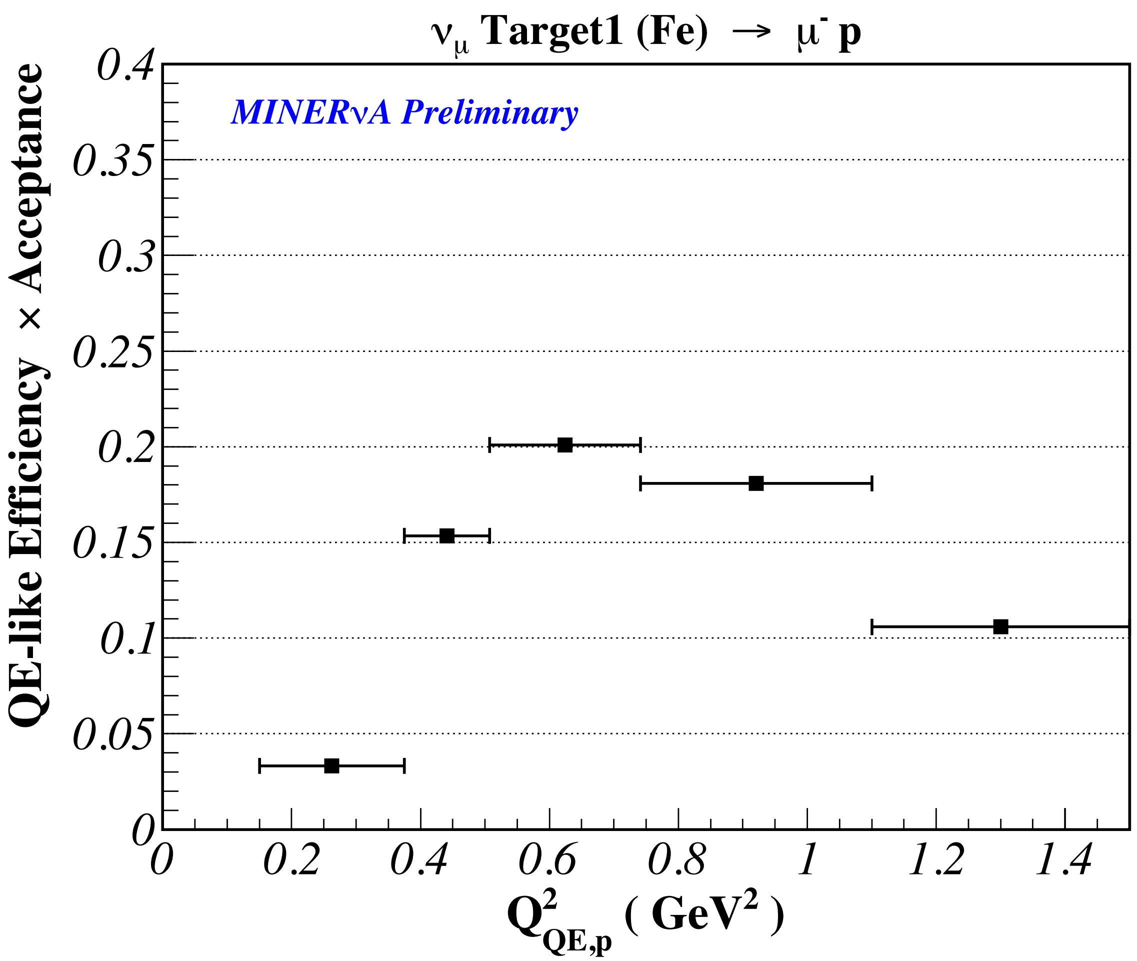
Targets

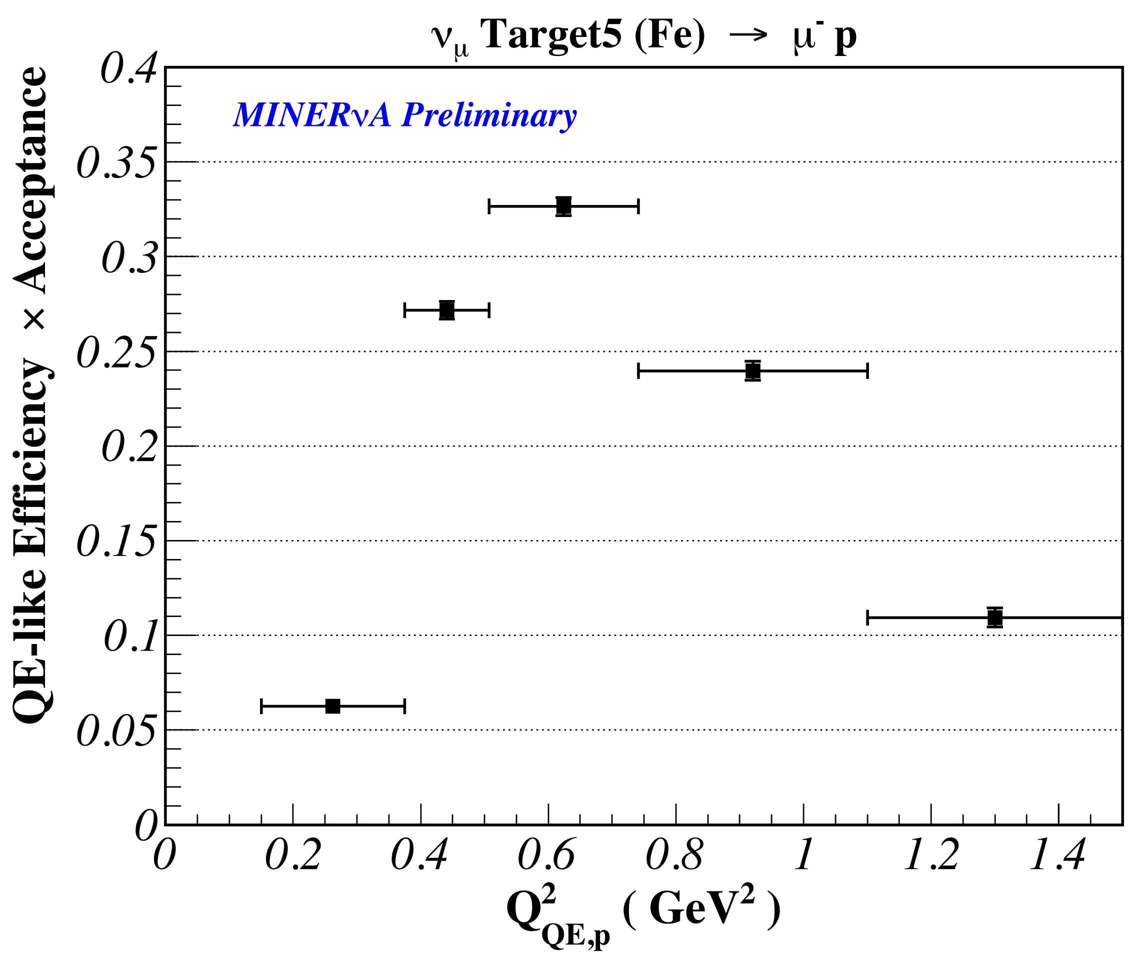
Efficiencies

- We have different efficiencies for each target, the most upstream targets, target1, target2 and target 3, are less efficient





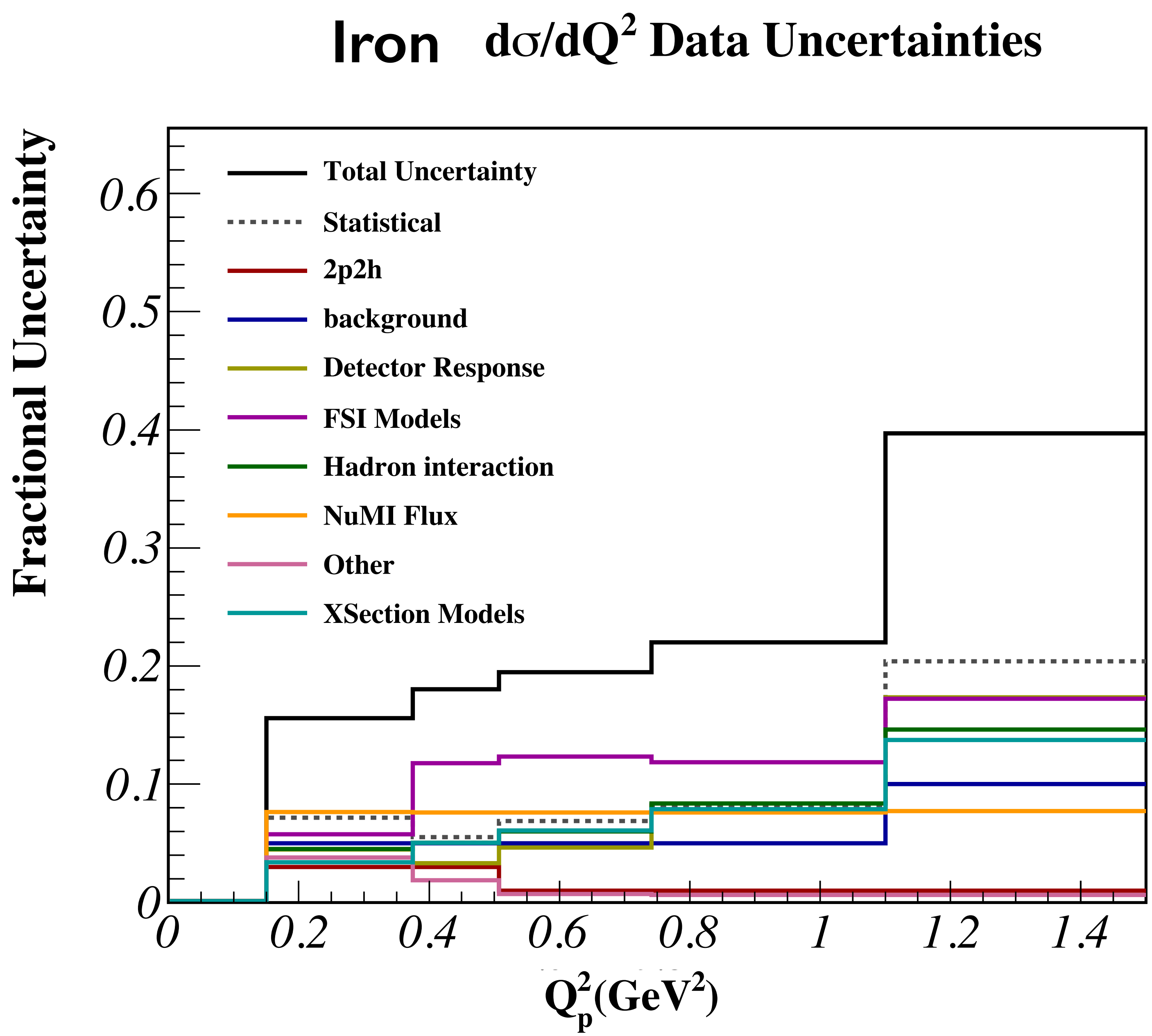




Systematics

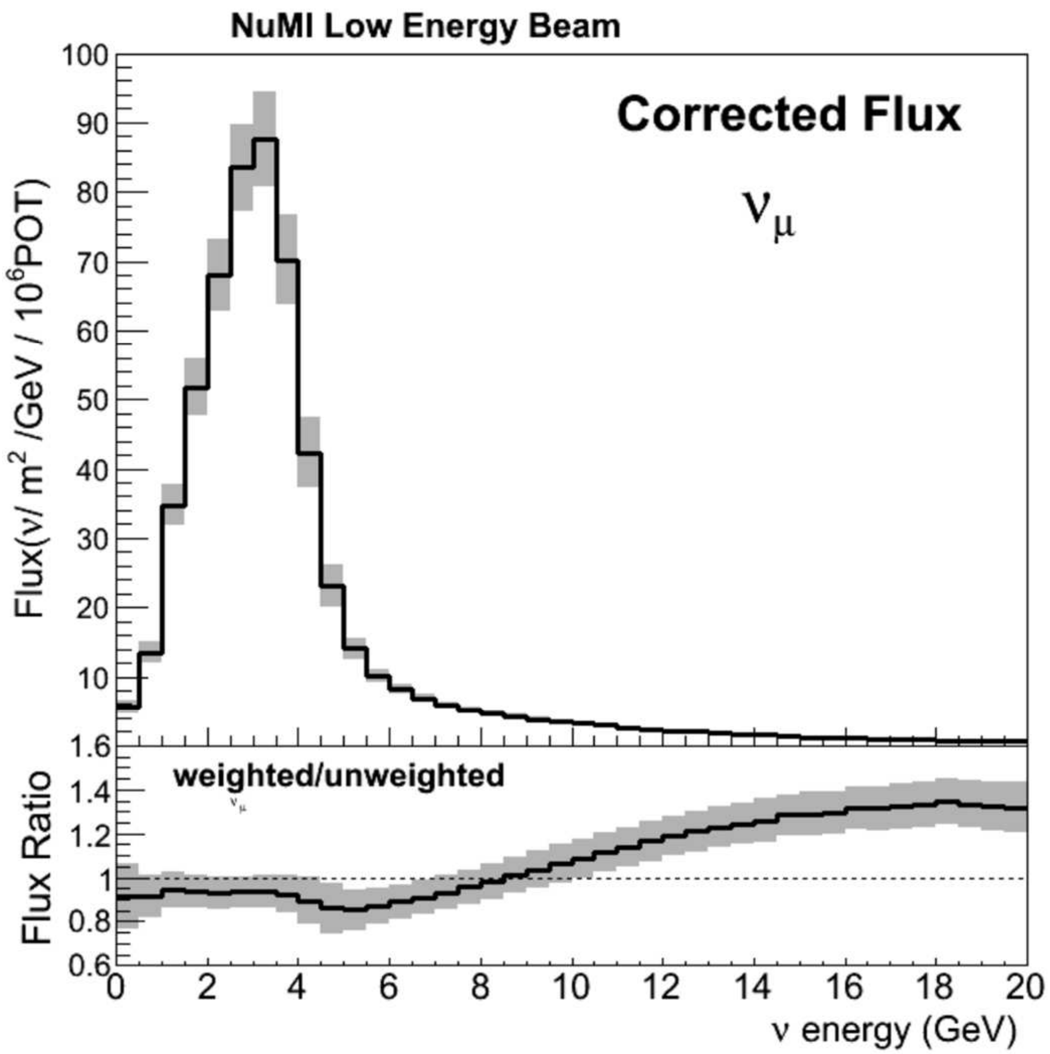
- We evaluated different systematics uncertainties
  - Flux
  - Detector response
  - Final state interactions
  - Hadron interactions
  - Cross section models

Iron

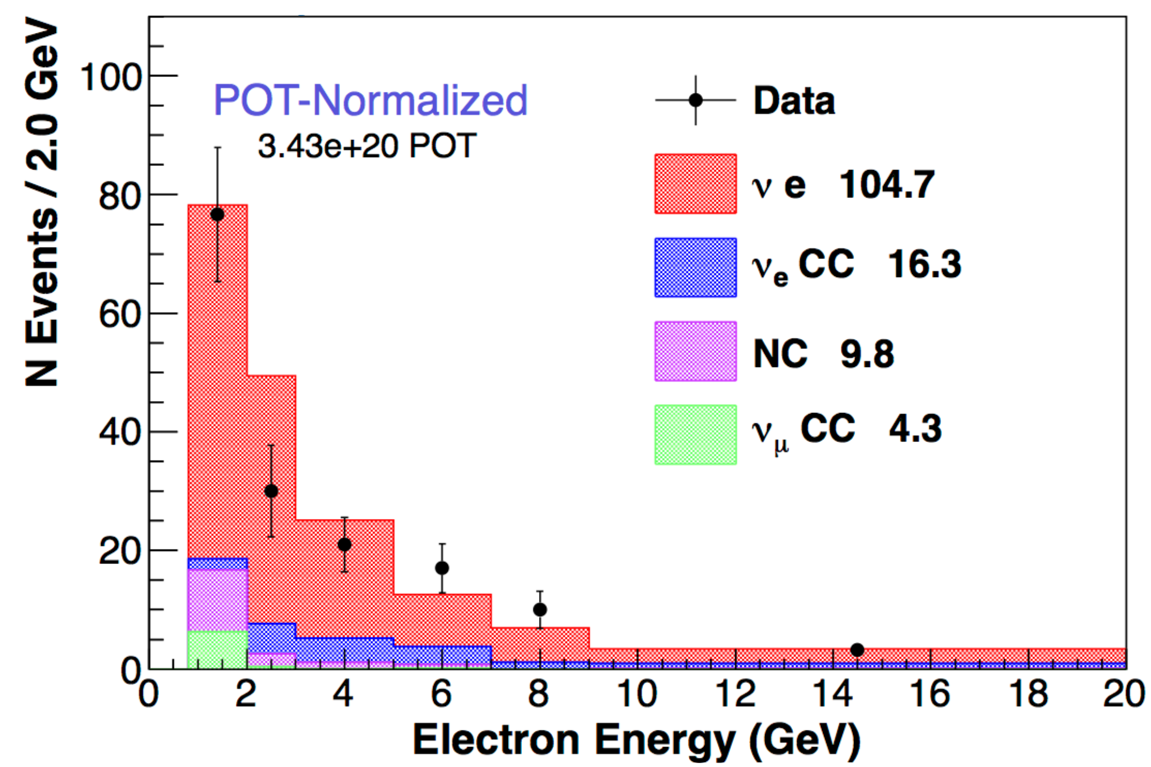


Flux Prediction

- Simulation has been tuned to hadron production data from NA49 and constrained using neutrino scattering on electrons



arXiv:1607.00707

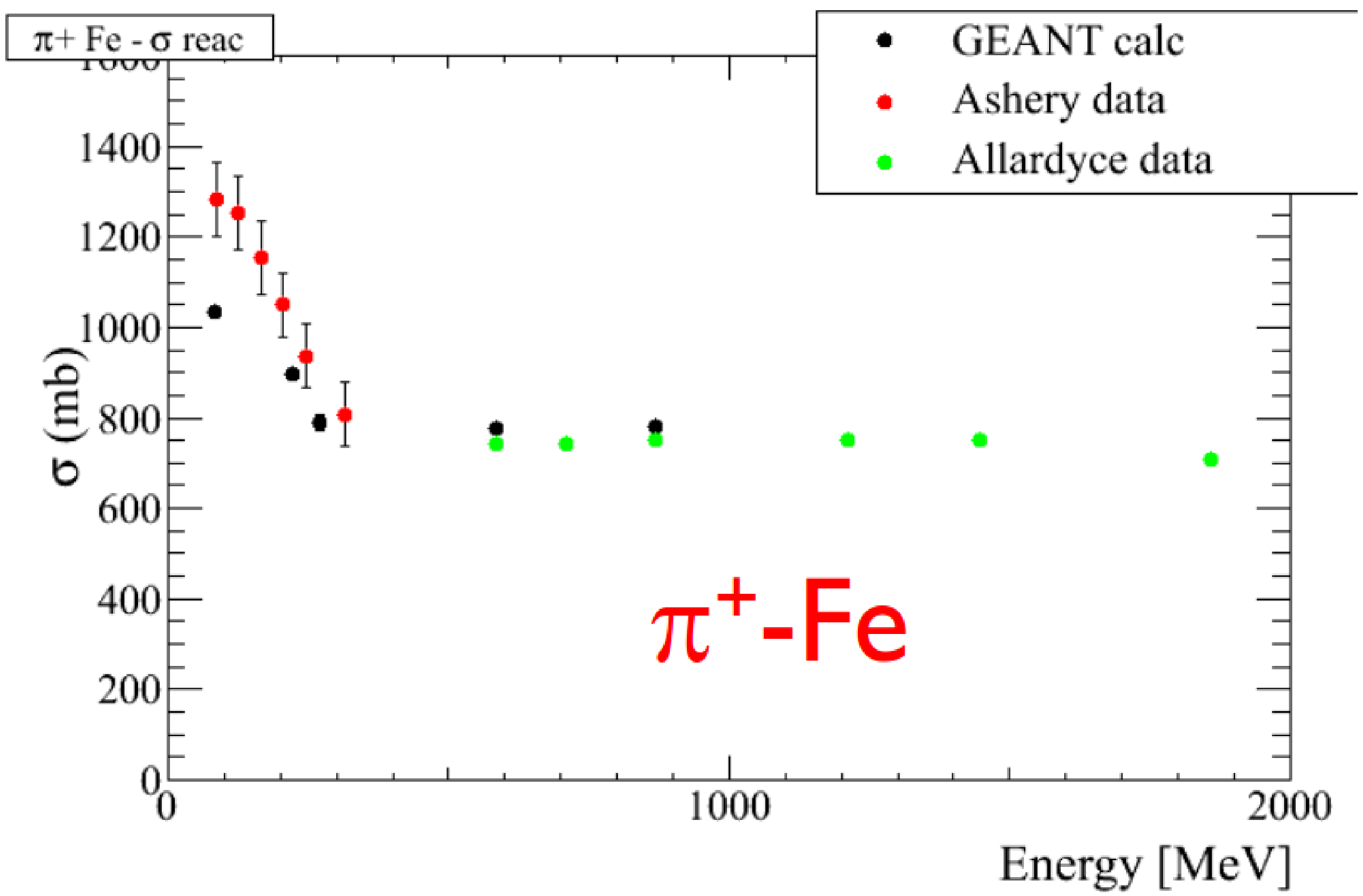


Phys. Rev. D 93, 112007 (2016)

Proton Interaction Systematic

- GEANT hadron cross sections differ from data
- In MC, we can reweight MC to account for the uncertainty in the cross section
- Evaluated for proton, neutron and pion
- Based on GEANT to data comparison we assign

δ = 10% in C
= 15% in Fe
= 20% in Pb



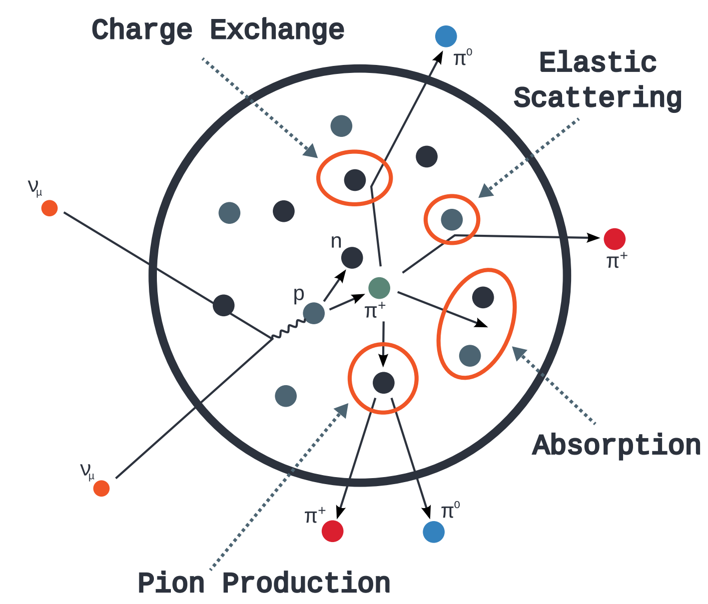
Phys. Rev. C23, 2173 (1981)

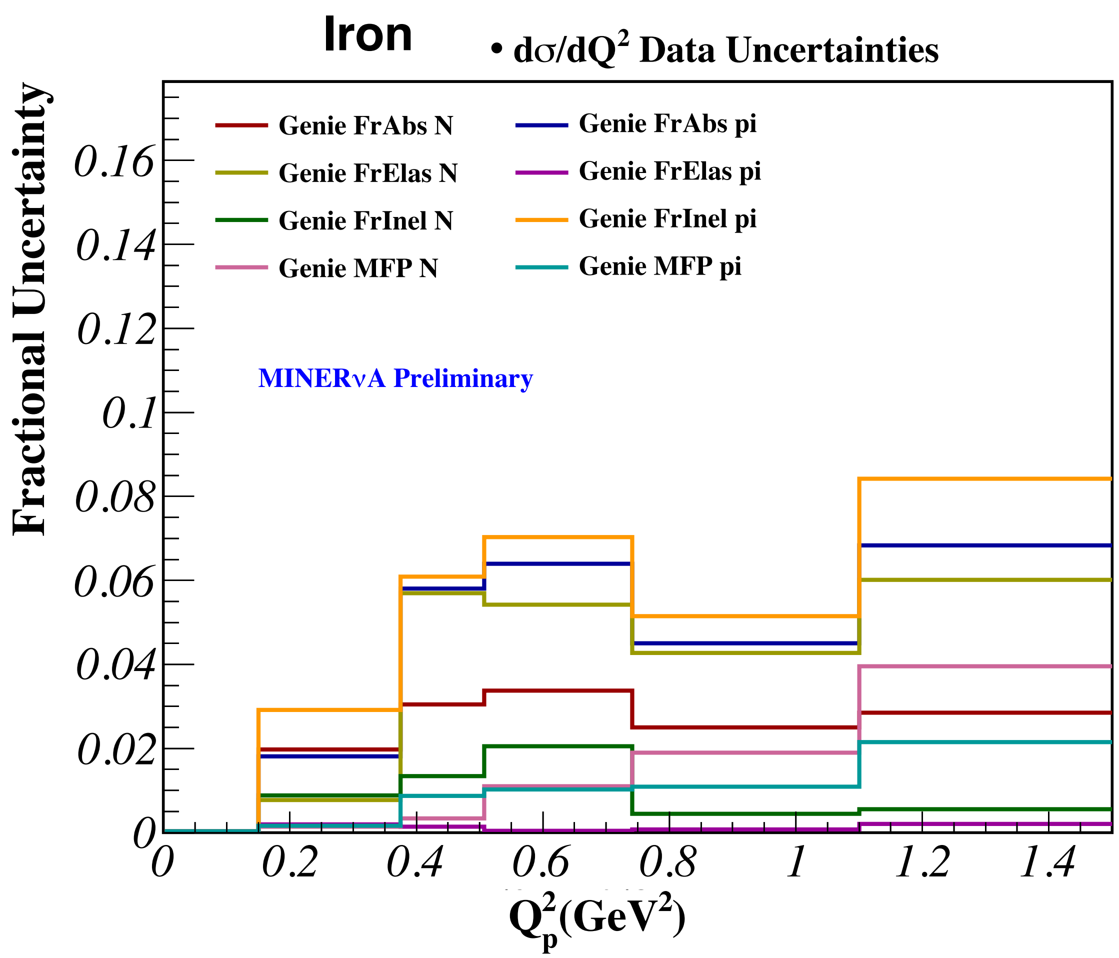
Fermilab

FSI Systematics

- Different final state interactions models are evaluated

Parameter	Uncertainty
pion/nucleon mean path	20%
pion/nucleon charge exchange	50%
pion absorption	30%
pion/nucleon inelastic cross section	40%



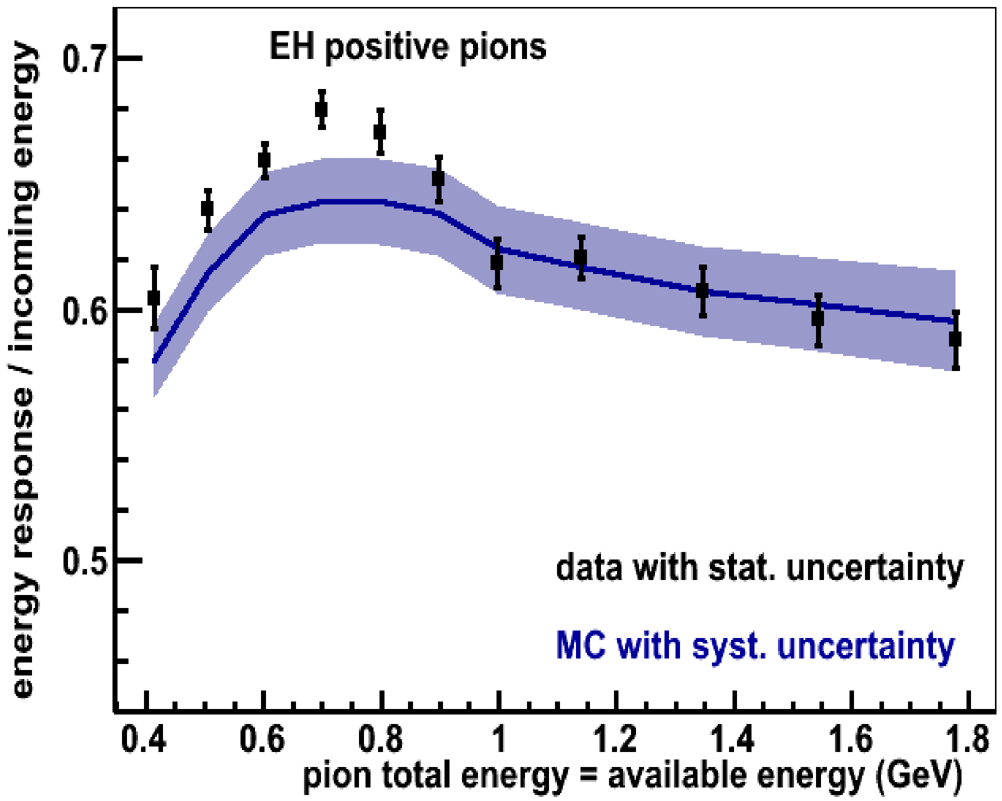


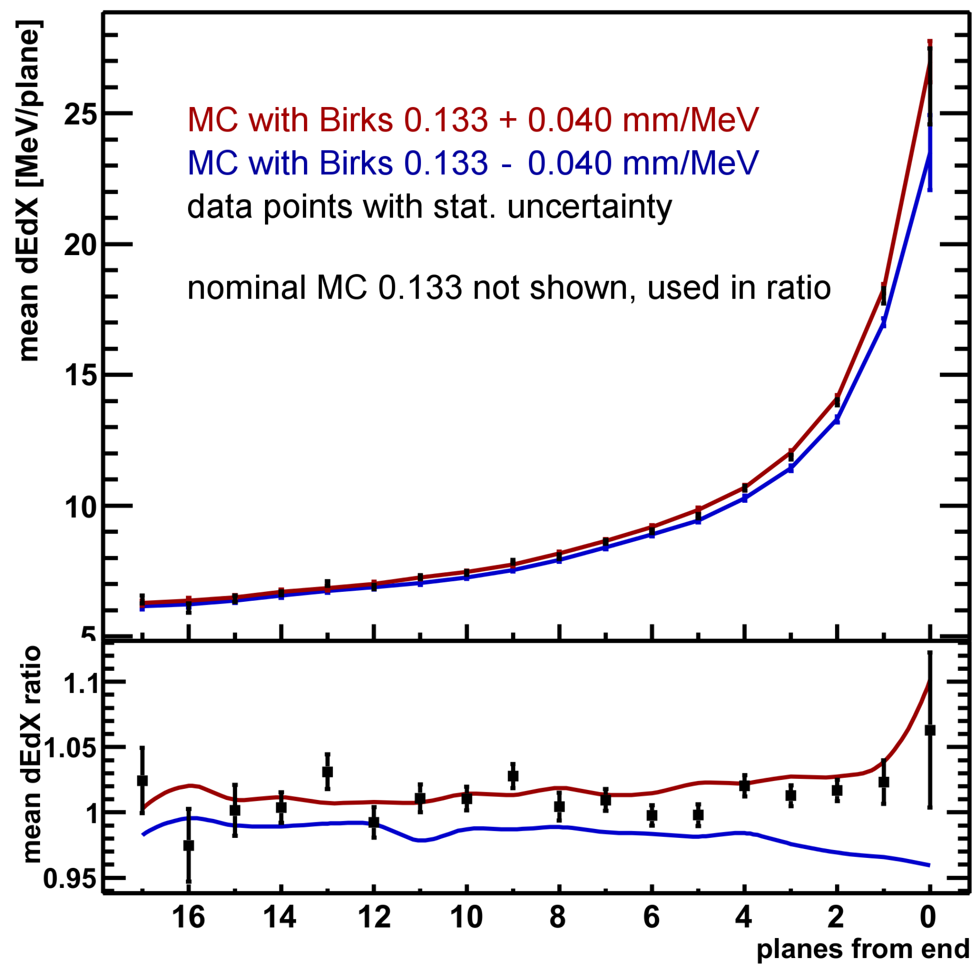
Dominant systematics: pion absorption and inelastic pion

Since the proton is very sensitive to FSI, this systematic enters primarily from the efficiency correction

Detector Response

- The MINERvA detector's hadronic energy response was measured at the Fermilab Test Beam Facility using small replica of MINERvA
- In addition to a Birk's law calculation, hadronic energy reconstruction uncertainty is estimated from difference between test beam data and GEANT simulation



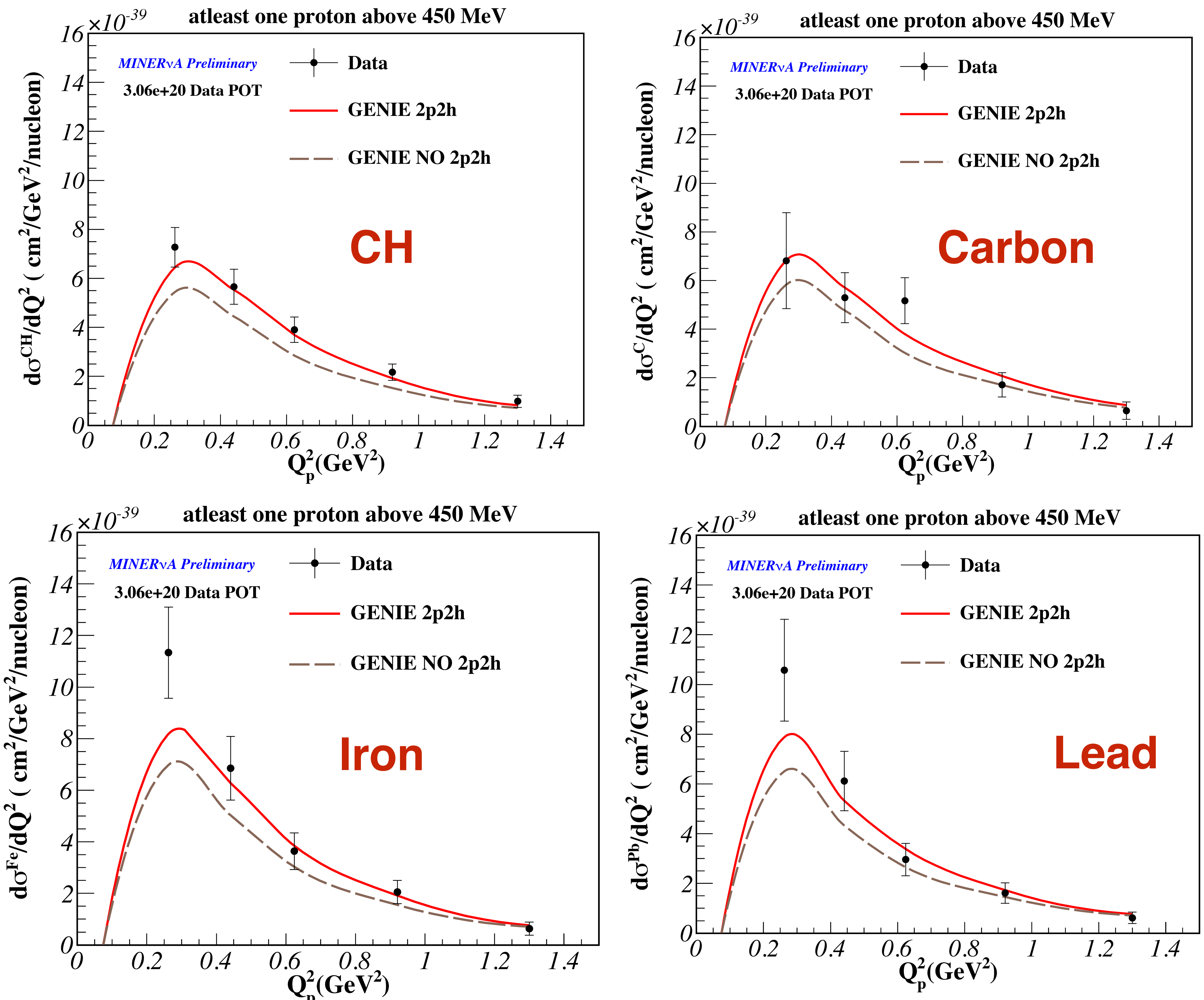


Nucl. Instrum. Meth. A789 (2015) 28-42

Results

Differential Cross Section Measurements

- Results compared against FSI GENIE with and without 2p2h simulation

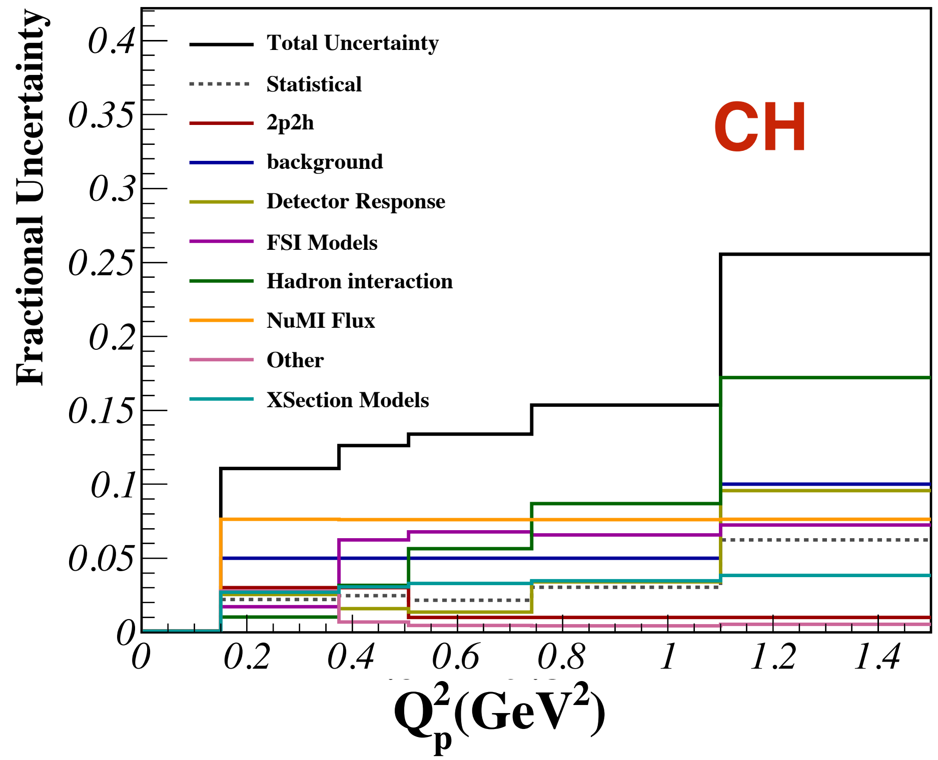


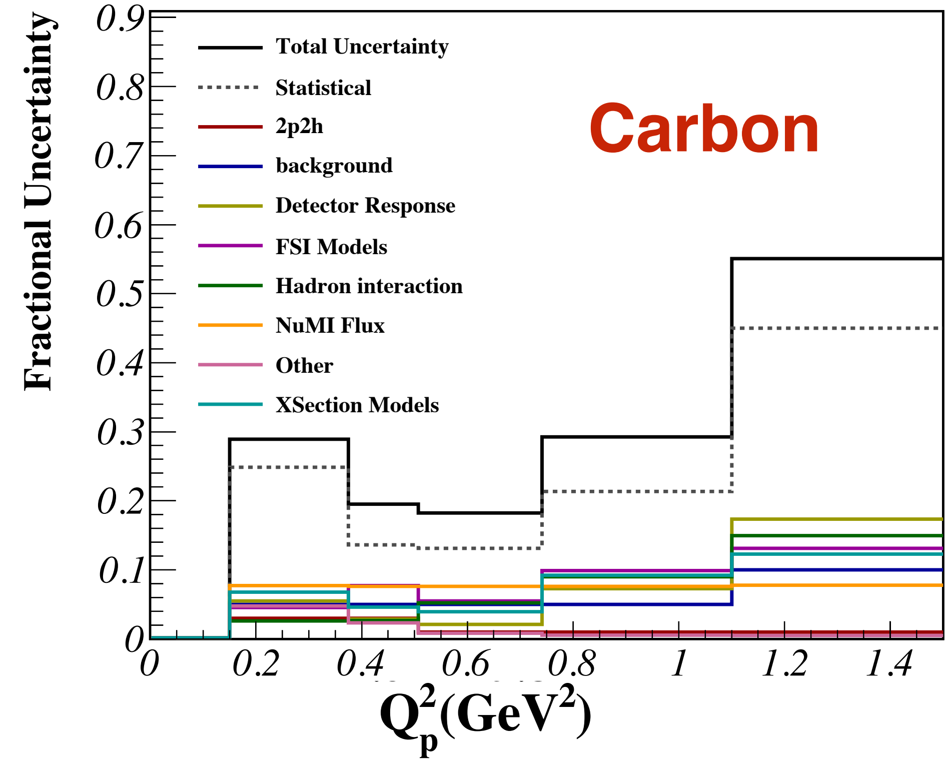
X^2/d.o.f

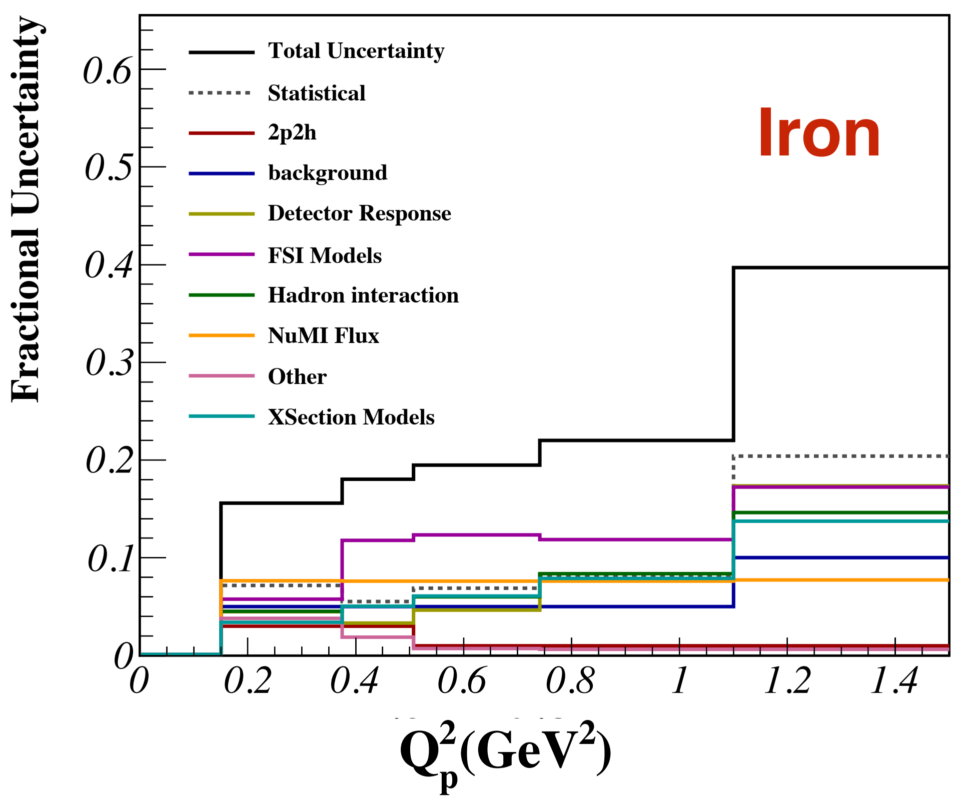
	carbon	iron	lead
GENIE	6/5	19/5	16/5
GENIE no 2p2h	11/5	64/5	41/5

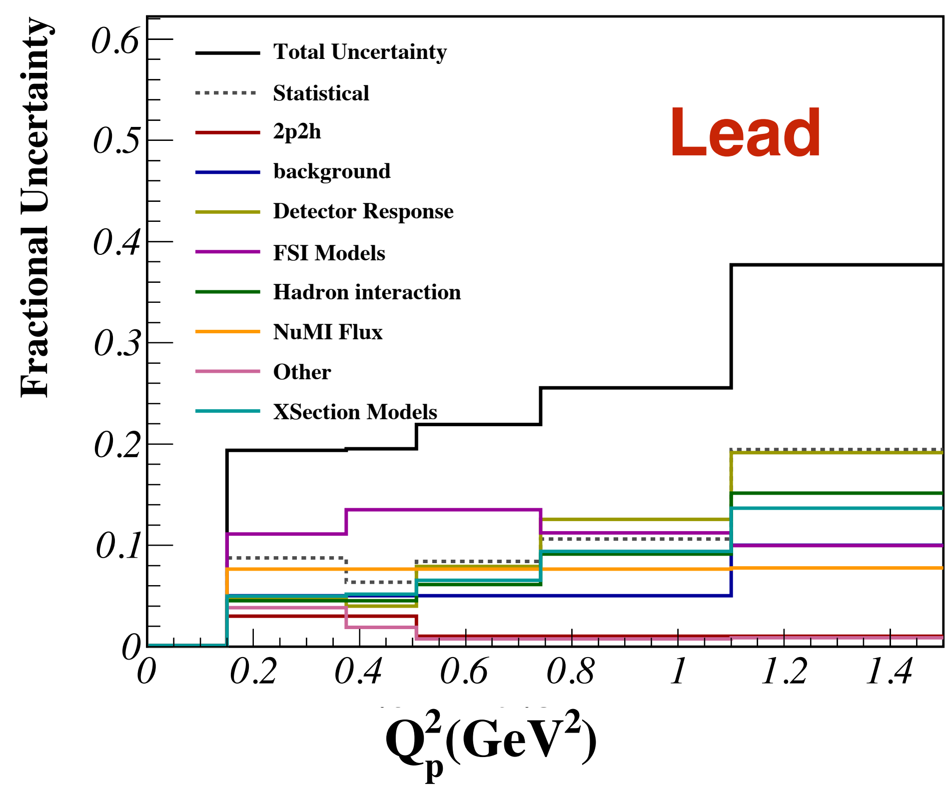
- Data prefers the simulation including 2p2h

Uncertainties



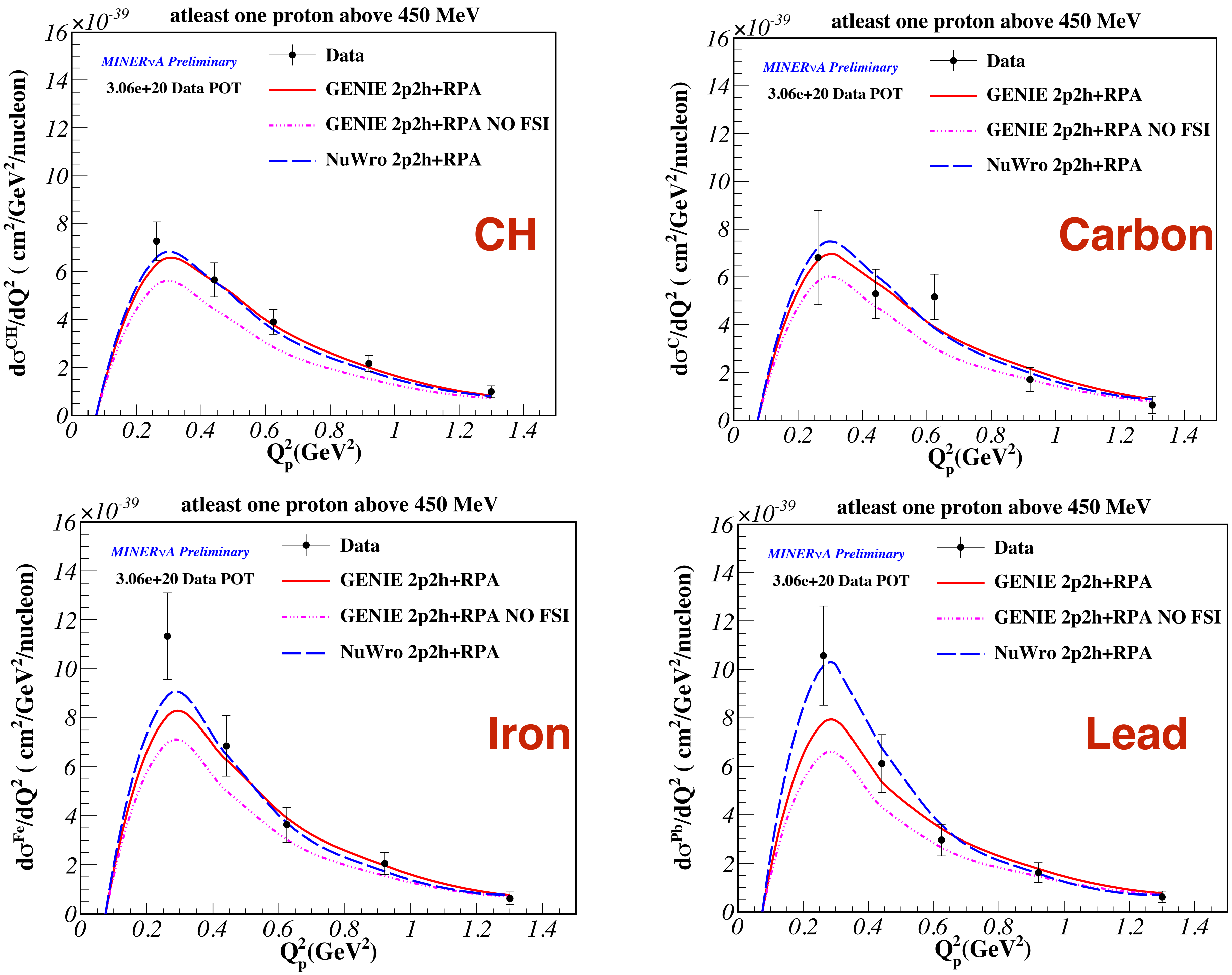






Comparing with Generators (GENIE vs NuWro)

- Data prefers the simulation with final state interactions



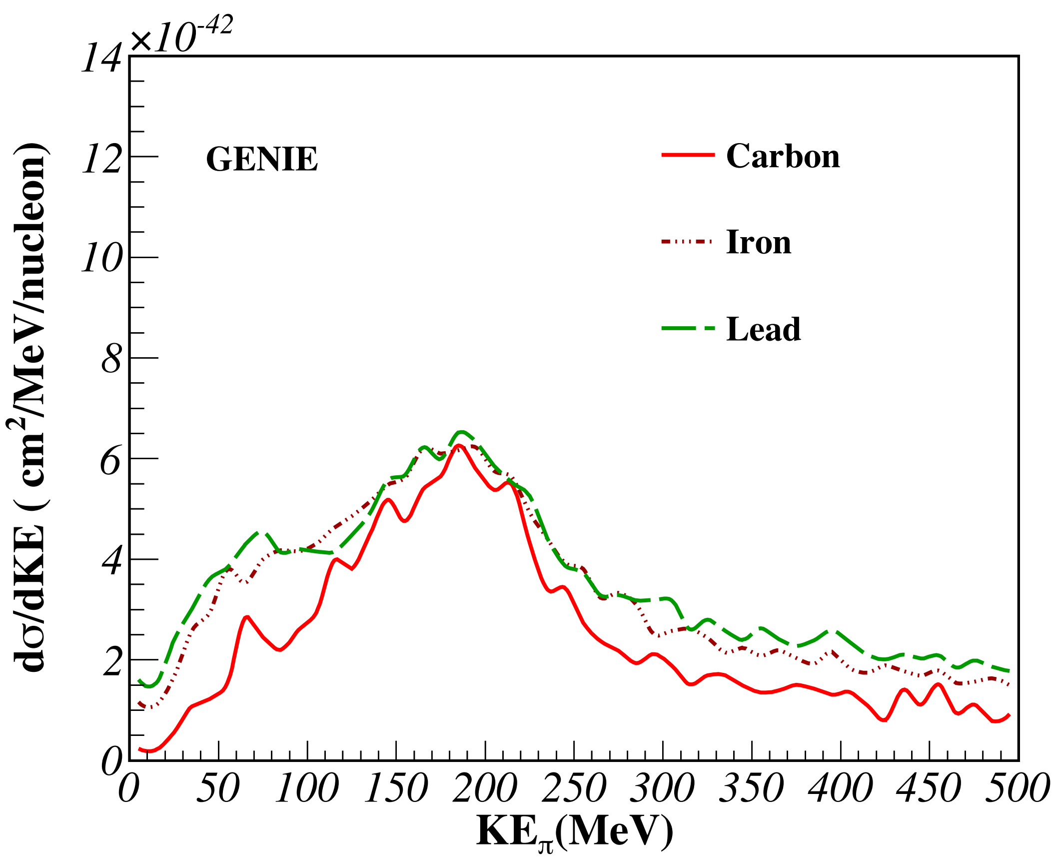
X^2/d.o.f

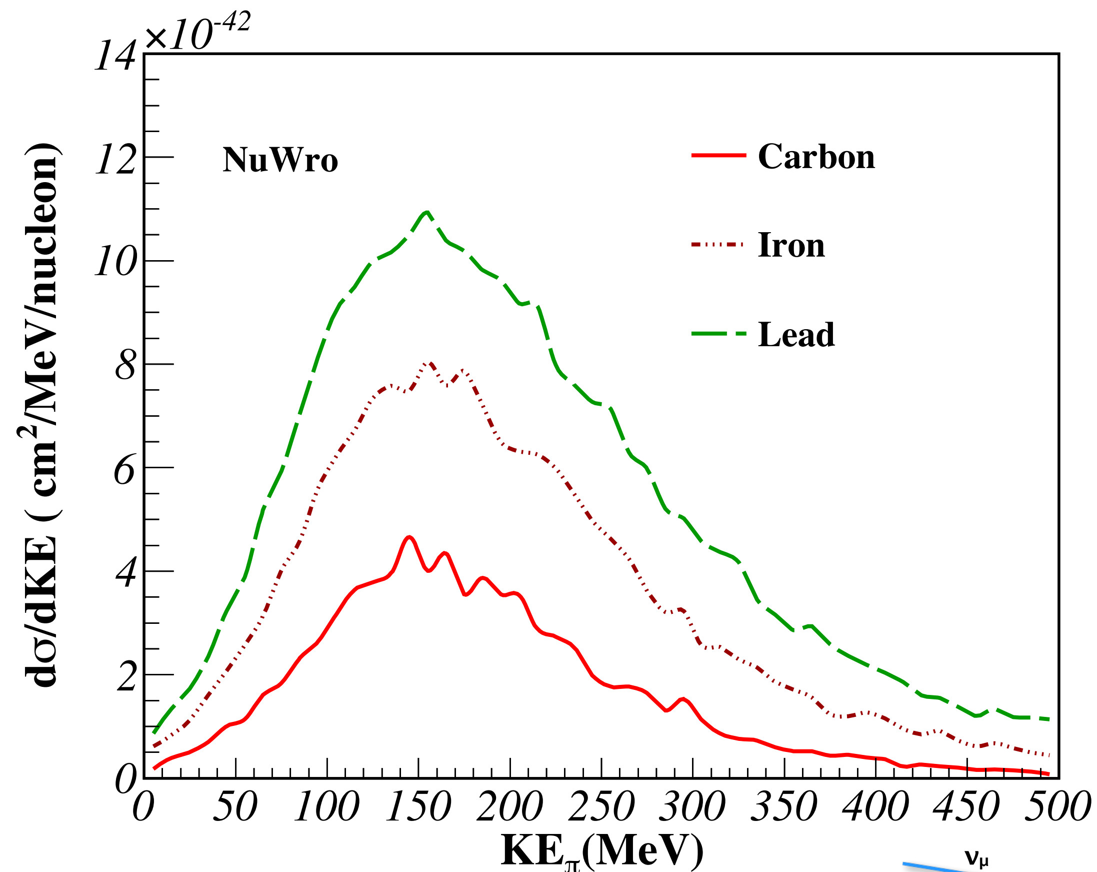
	carbon	iron	lead
GENIE	5.9/5	19.9/5	17.5/5
NuWro	6/5	14.6/5	11.1/5

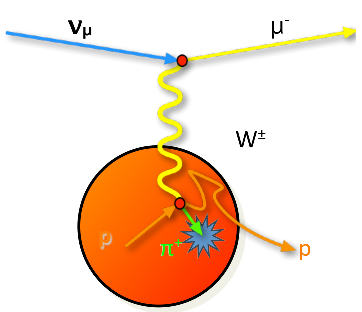
- The A dependence in NuWro seems to be more favored by the data

GENIE and NuWro

- The one pion absorption difference between GENIE and NuWro is contributing to the A dependence



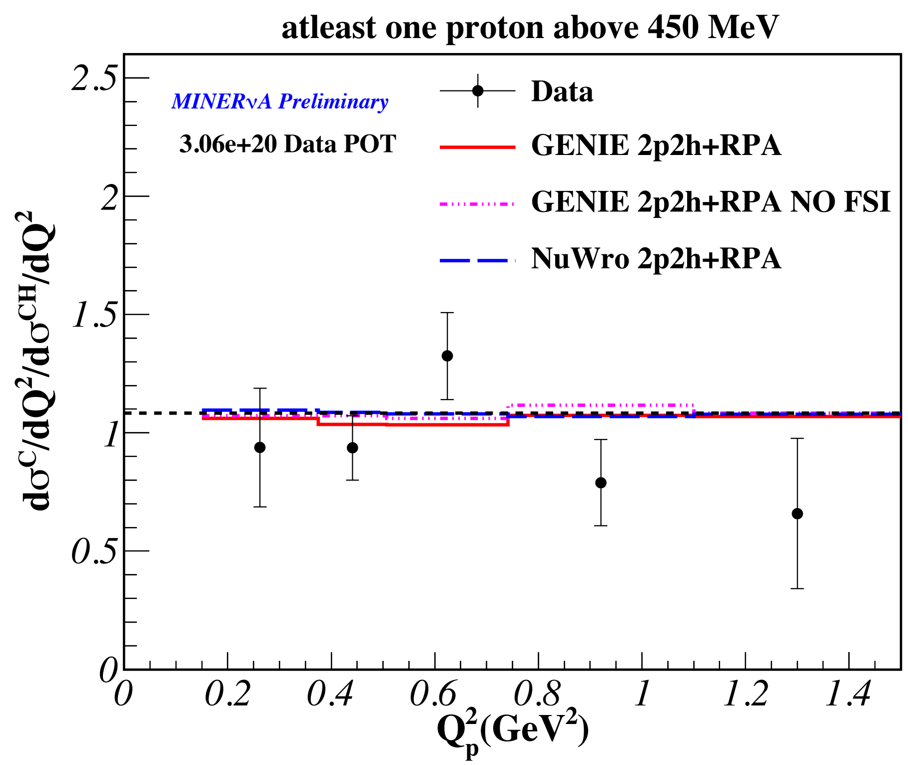




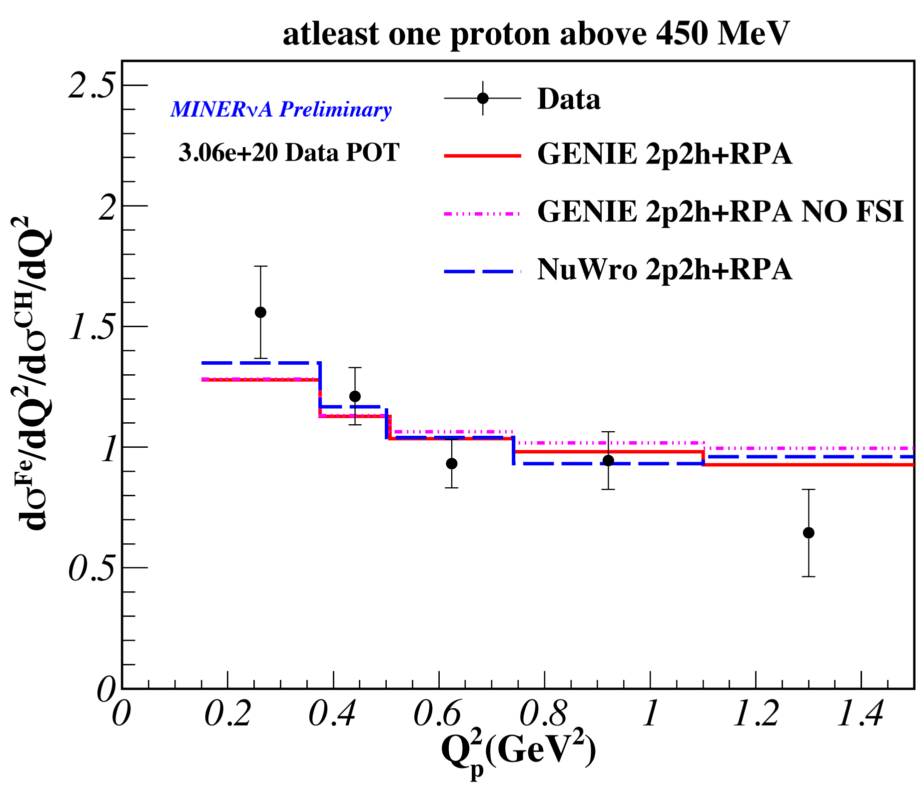
- Comparisons of GENIE and NuWro without FSI showed some disagreement for the inelastic component from the total quasi-elastic

Ratios Carbon/Iron/Lead to Scintillator

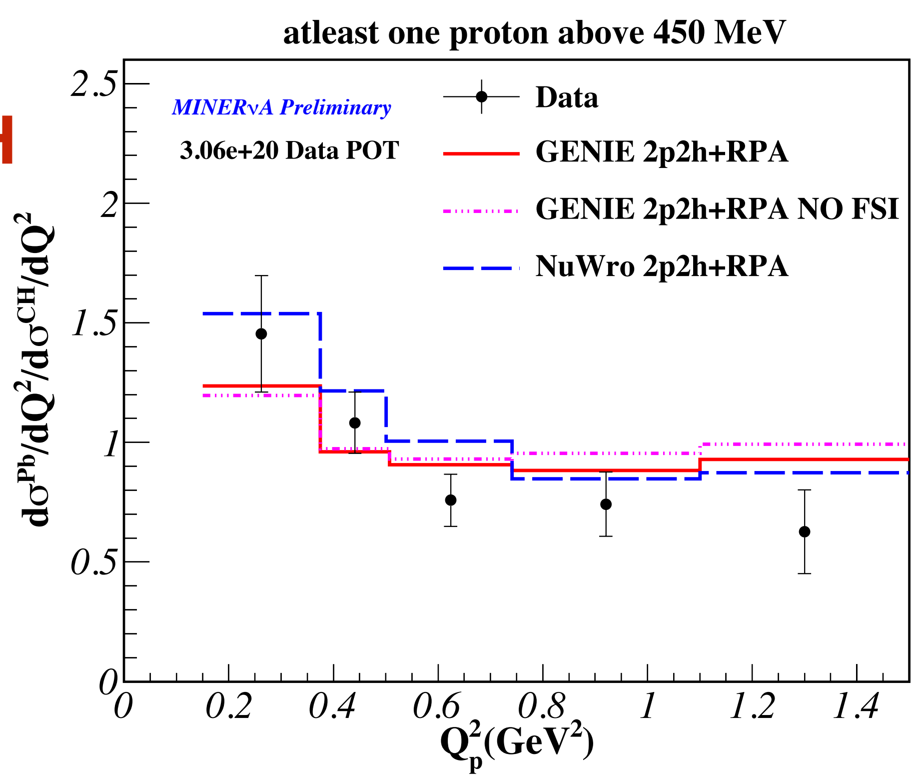
Carbon/CH



Iron/CH

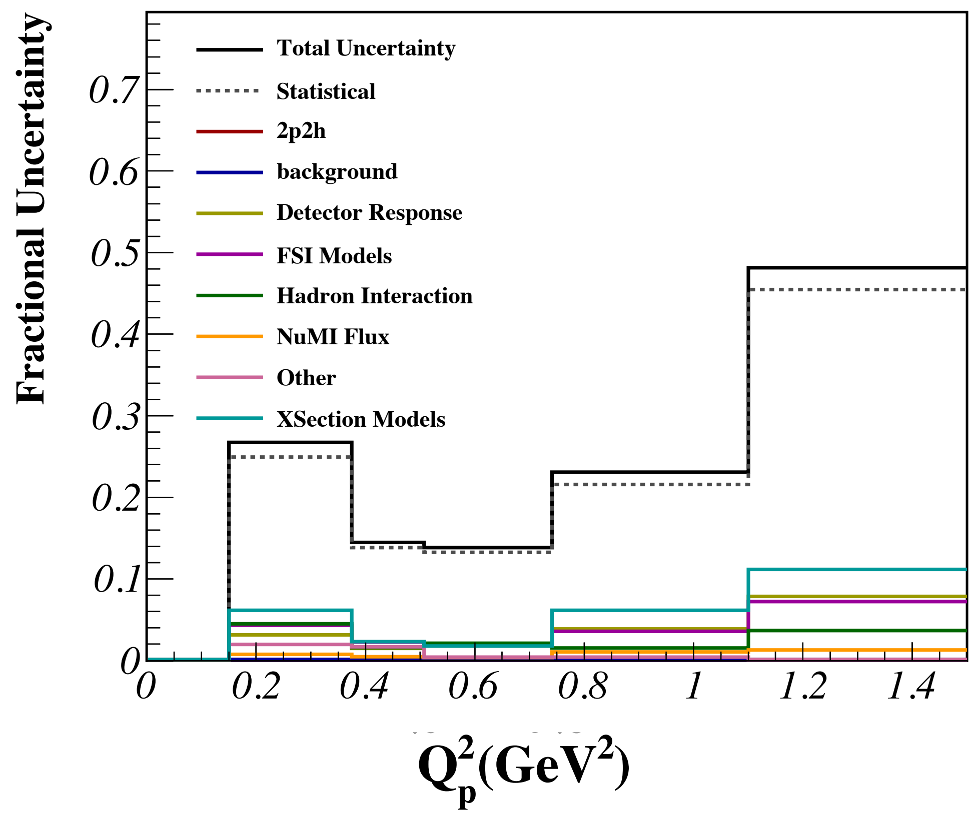


Lead/CH

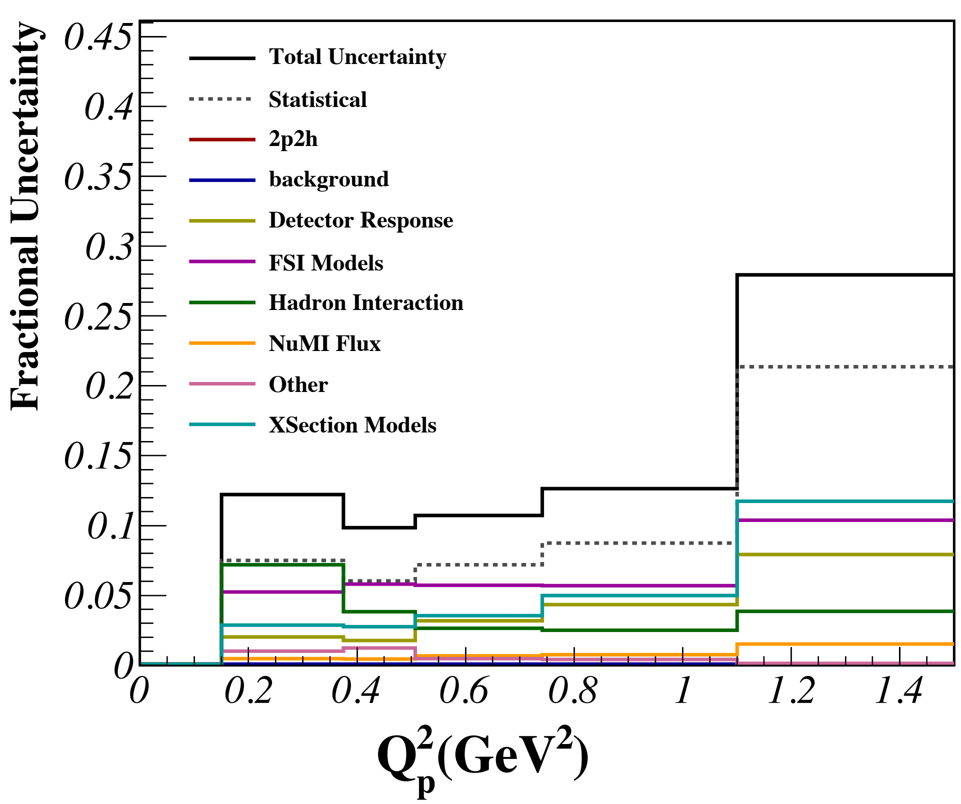


Uncertainties

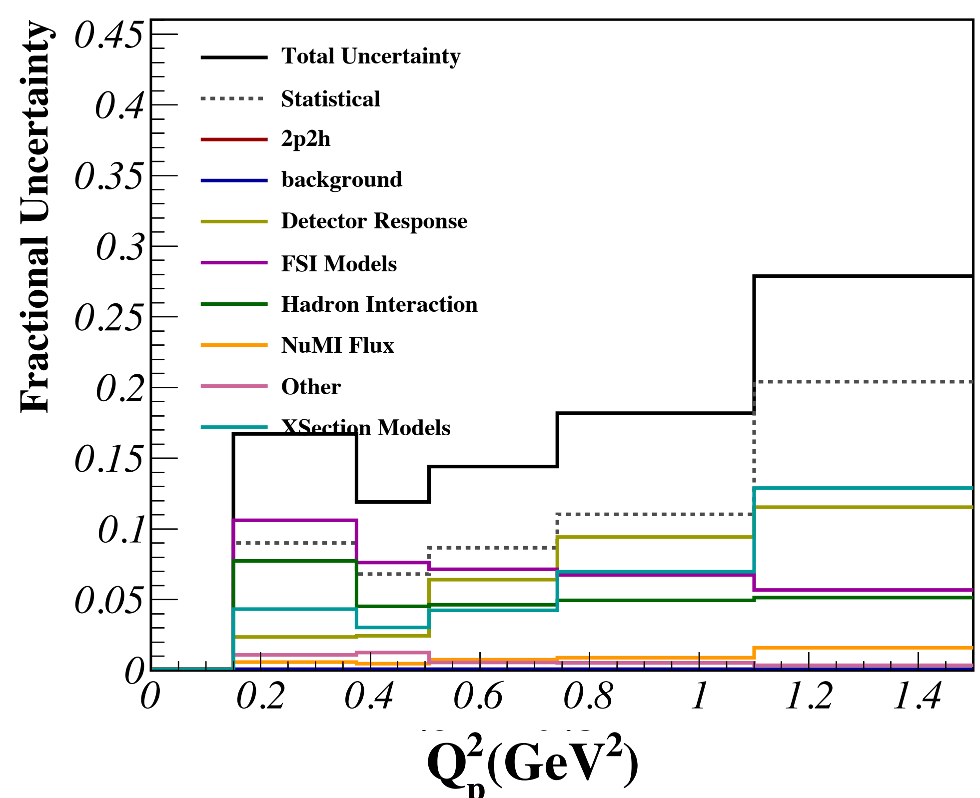
Carbon/CH



Iron/CH

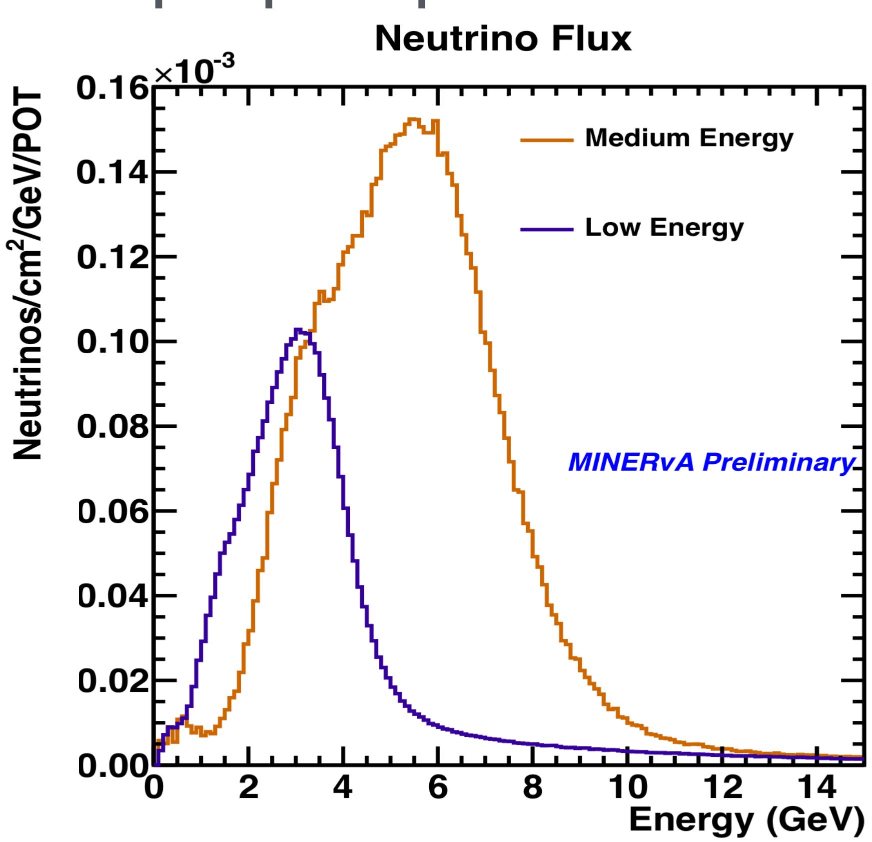


Lead/CH



Future

- Nuclear effects using different variables with the same muon+proton sample, arXiv: 1608.04655
- Measurements of quasi-elastic on iron, lead, and carbon using the NuMI medium energy beam yielding high statistics and a larger Q^2 range
  - We have over 10E20POT in the medium energy beam and plan to take advantage of that data set in the future
- Many of the exclusive measurements done for the tracker will be performed with the nuclear targets, for example pion production measurements



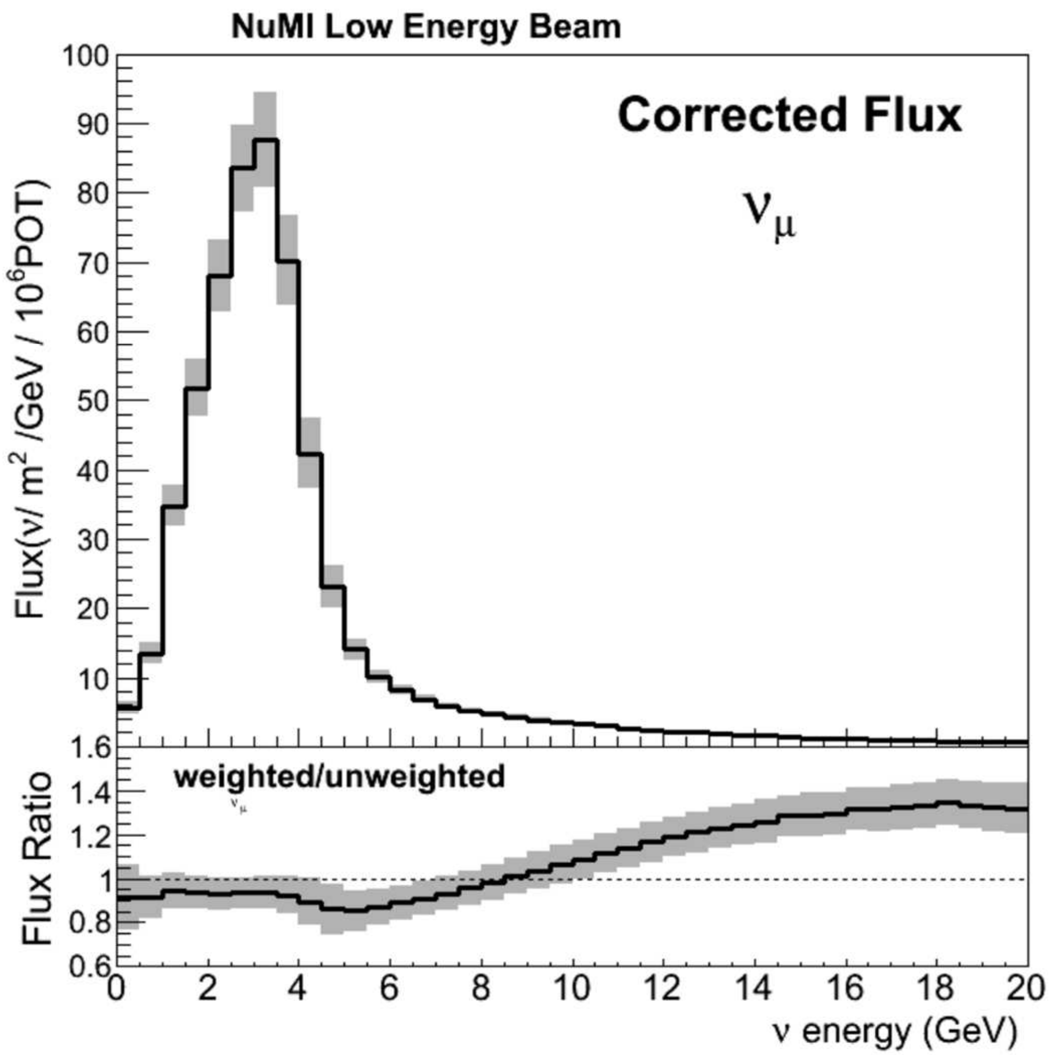
Fermilab

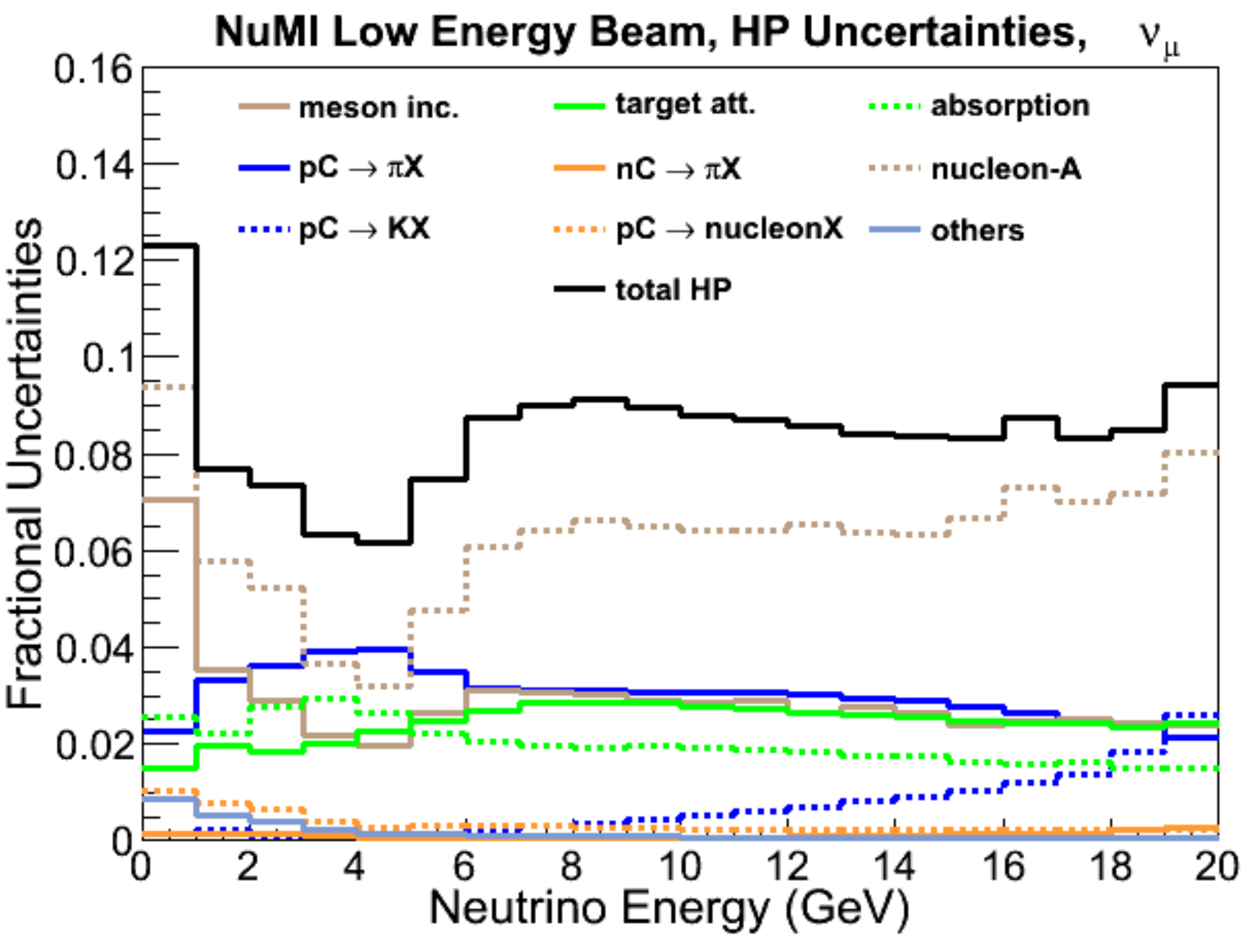
Conclusions

- We report new measurements of quasi-elastic like events on multiple nuclei (carbon, iron and lead) in an identical neutrino beam
- Both FSI effects and the 2p2h effect take energy from the leptonic system (2p2h) or pions (FSI) and move it into nucleons, which then affect the energy estimation in neutrino oscillation measurements
- We are measuring this directly by looking at muon+proton events
- Data prefers the simulated enhancement that the 2p2h model predicts
- There are similar 2p2h predictions in GENIE and NuWro, but different FSI predictions as a function of A. Data prefers NuWro
- These results will allow us to provide a constraint on the A dependence of nuclear effects
- Oscillation experiments depend on modeling nuclear effects correctly for precision oscillation measurements!

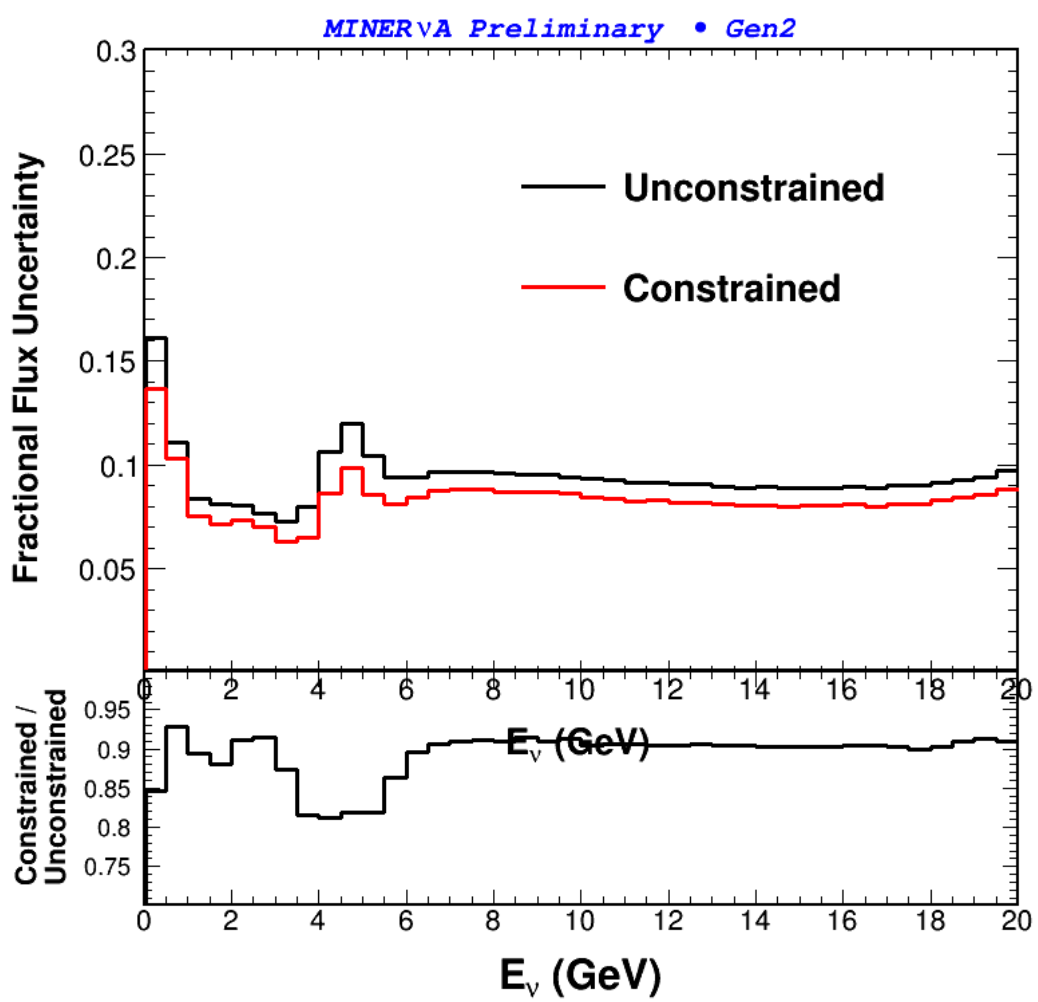
Thanks

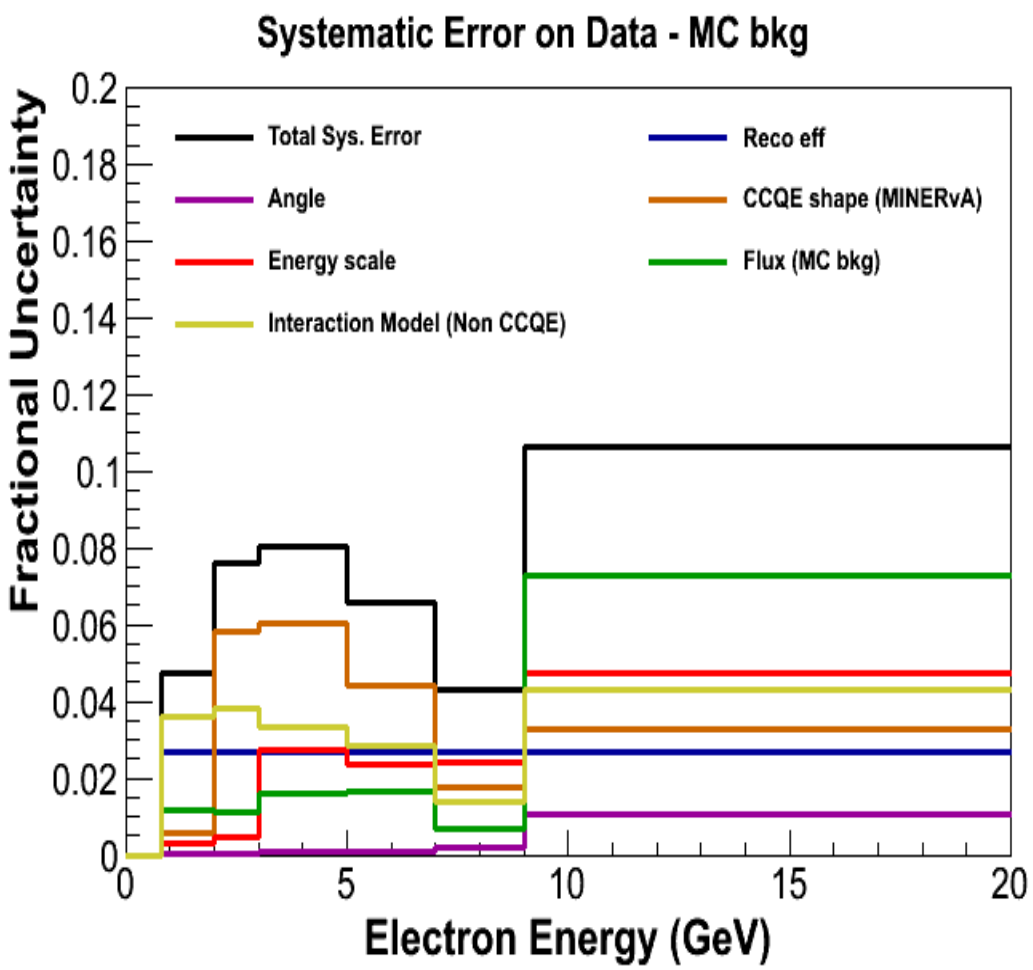
The NuMI Flux





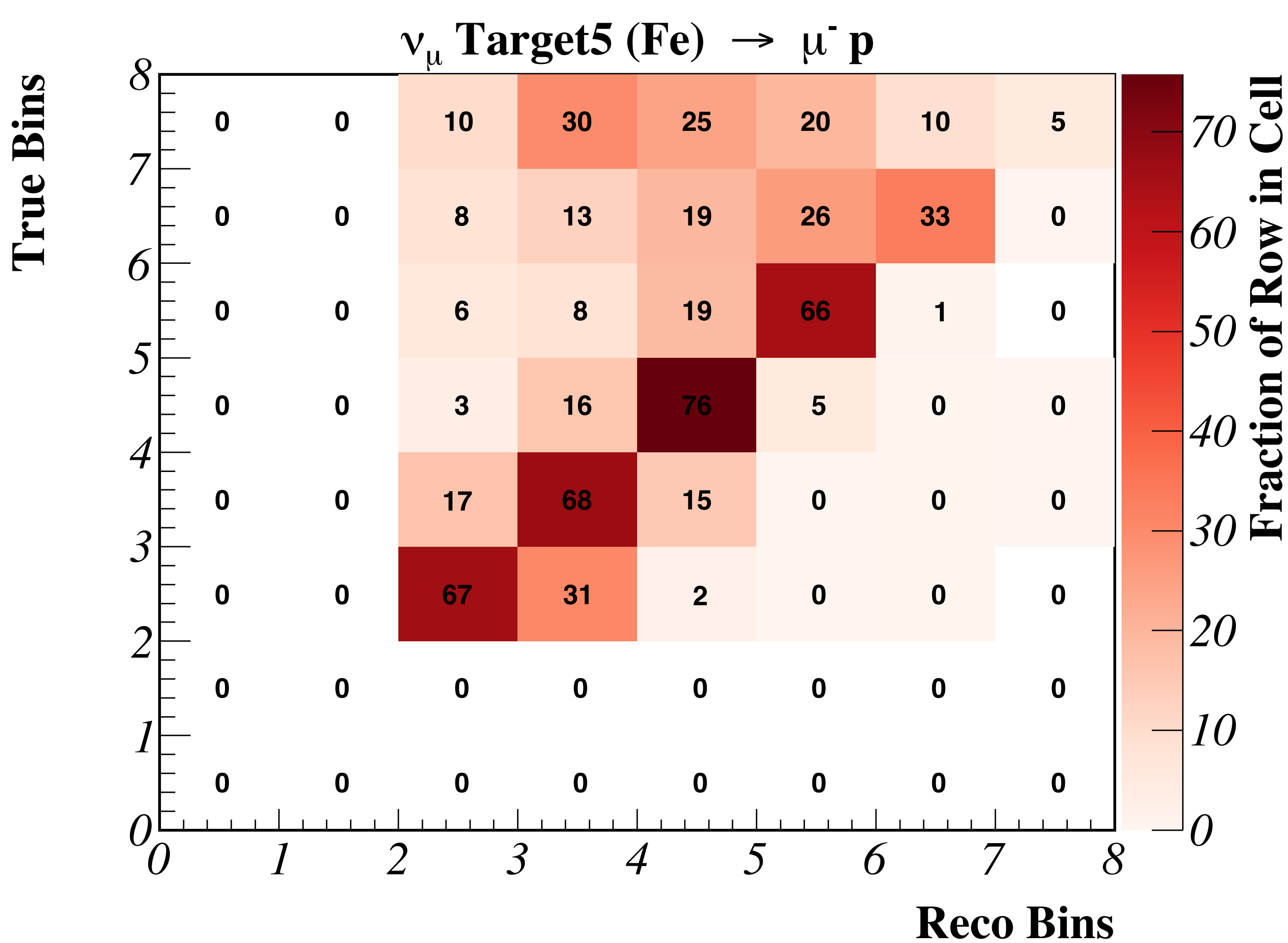
Neutrino Electron Scattering

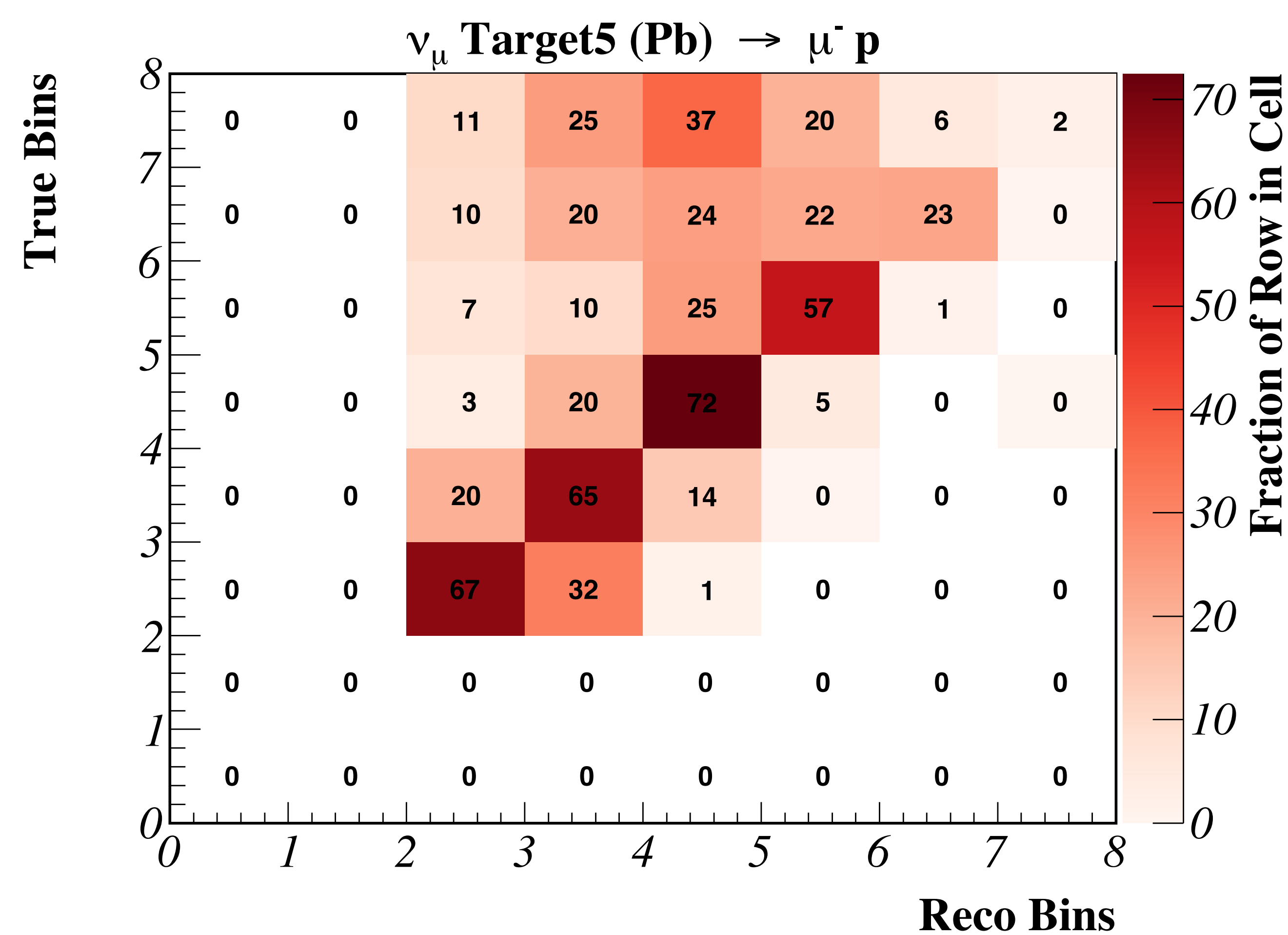




Phys. Rev. D 93, 112007 (2016)

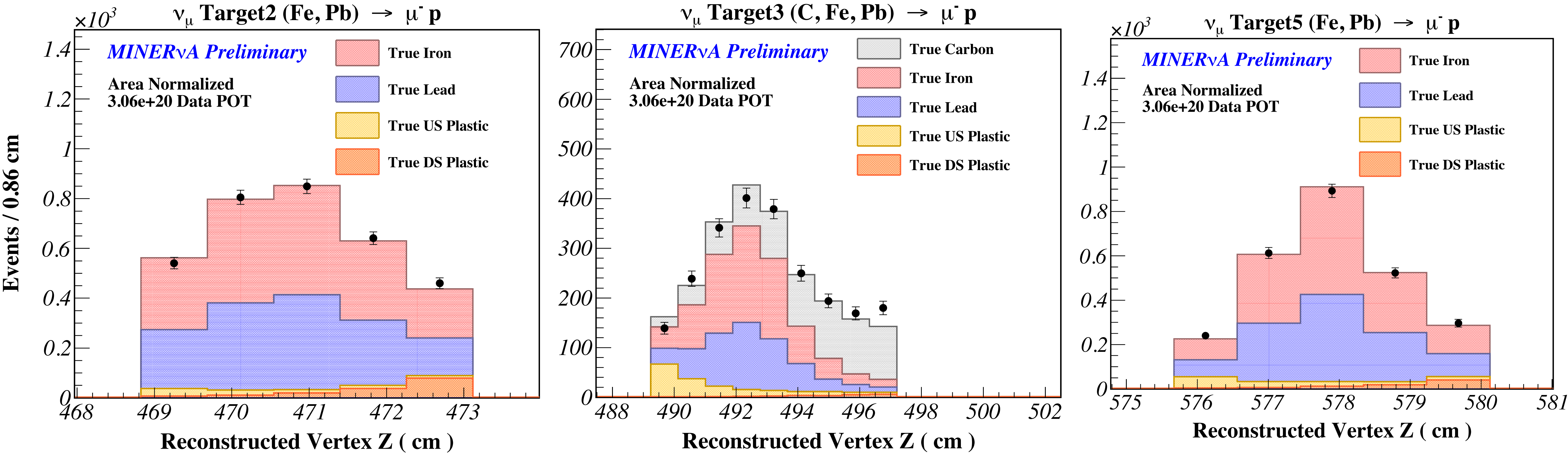
Migration Matrices





Reconstructed Z Positons

- Selected events in each of the nuclei and the scintillator background



- For events passing the analysis selection cuts