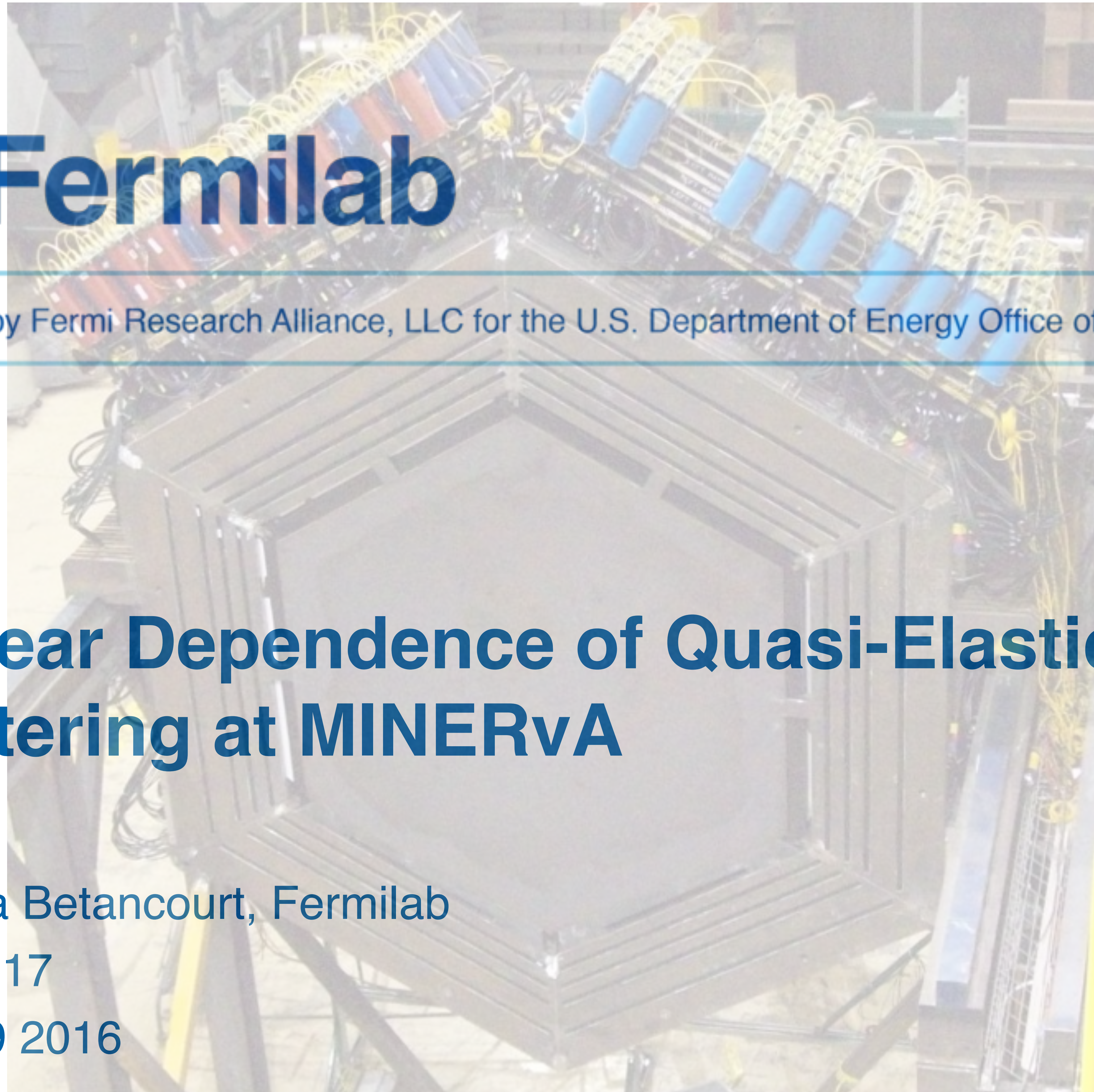

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Nuclear Dependence of Quasi-Elastic Scattering at MINERvA

Minerba Betancourt, Fermilab

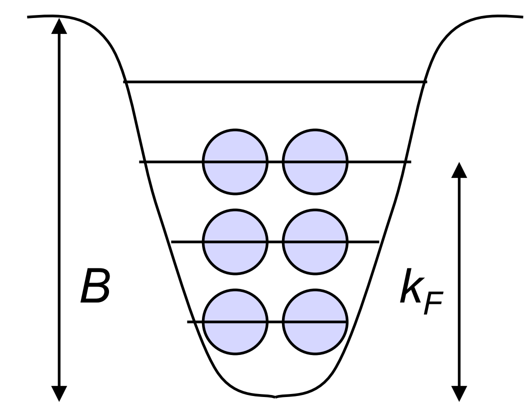
Nuint2017

June 29 2016

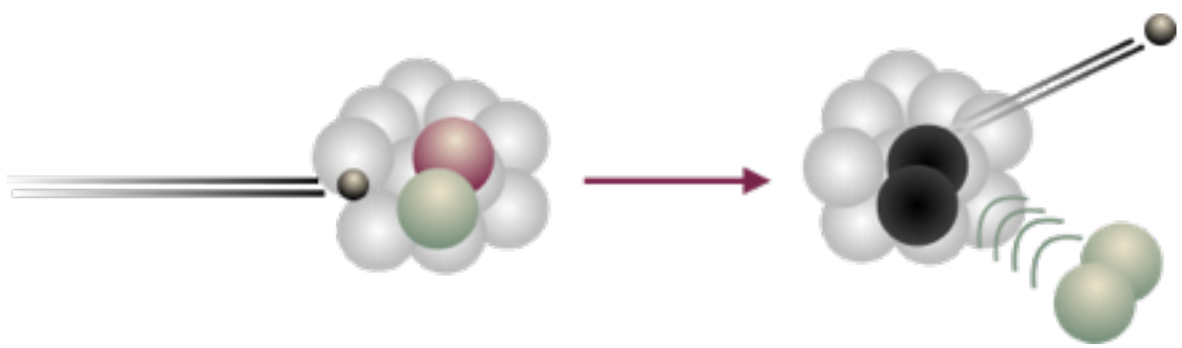
Introduction

- Nuclear effects are very important to understand for the precision oscillation measurements, a short list of nuclear effects:
  - Fermi motion
  - Pauli blocking
  - Multi nucleon interactions
  - Final state interactions

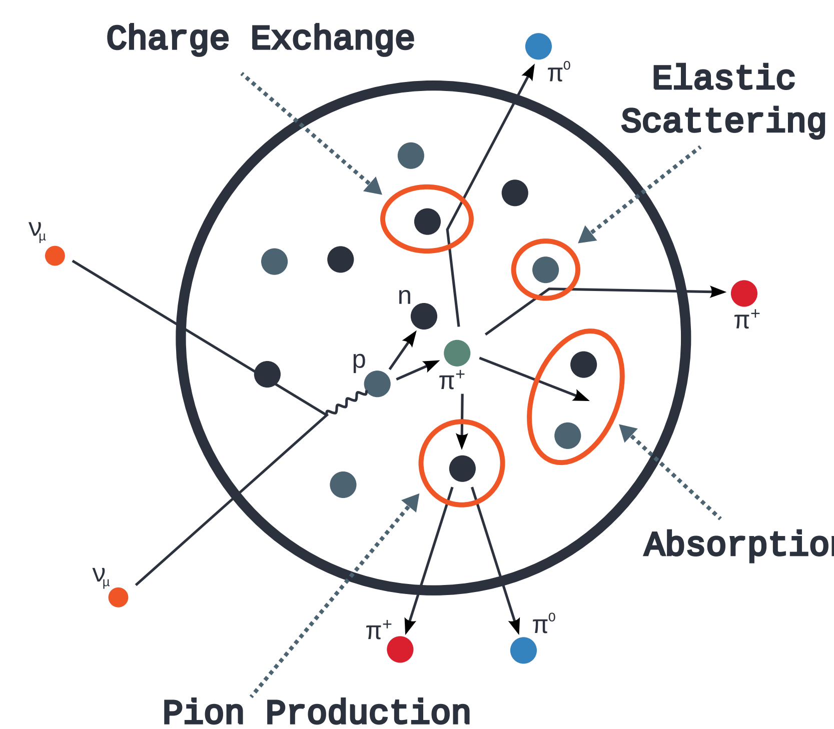
Fermi motion



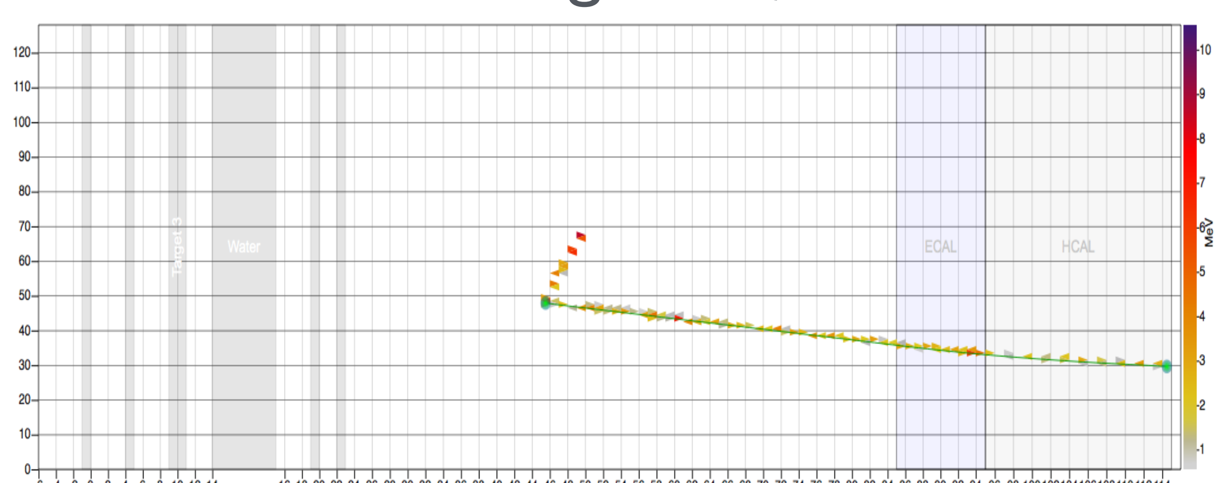
Multi nucleon interactions



Final State Interactions (FSI)



- What can we learn using CCQE?



Introduction

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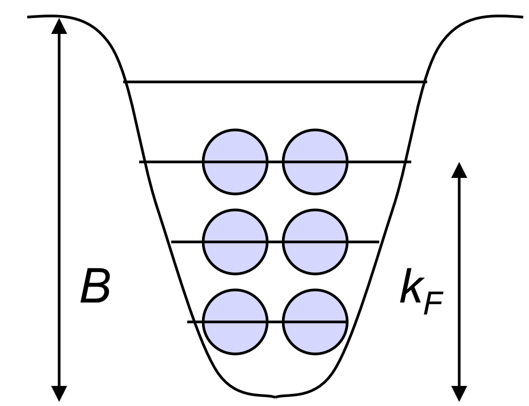
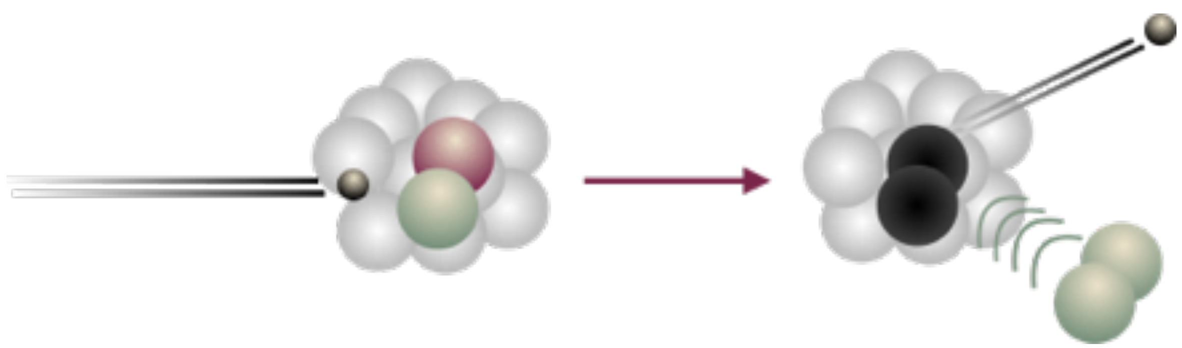
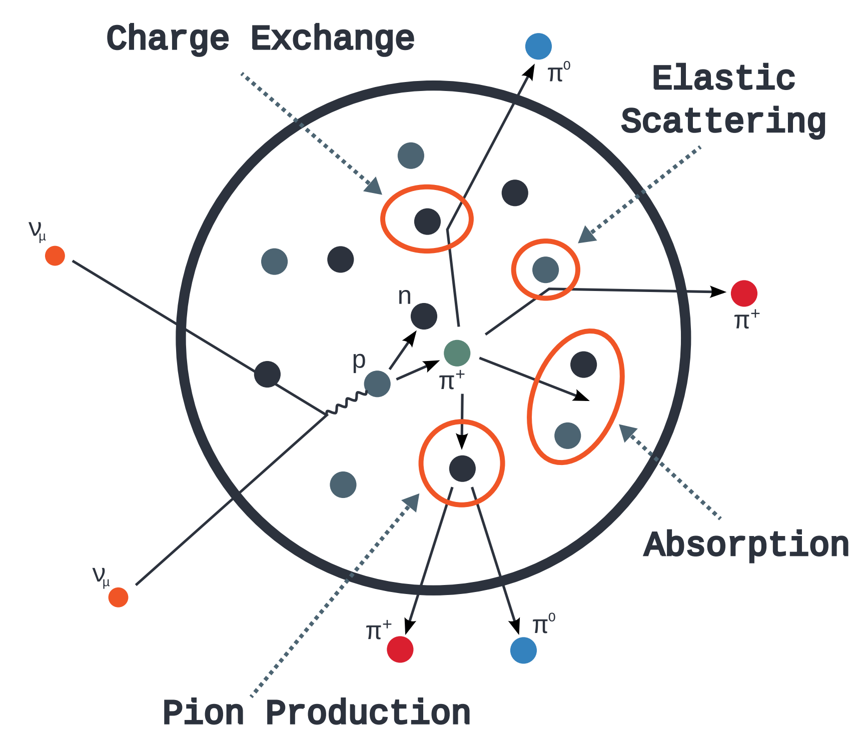
Fermi motion



Multi nucleon interactions



Final State Interactions (FSI)



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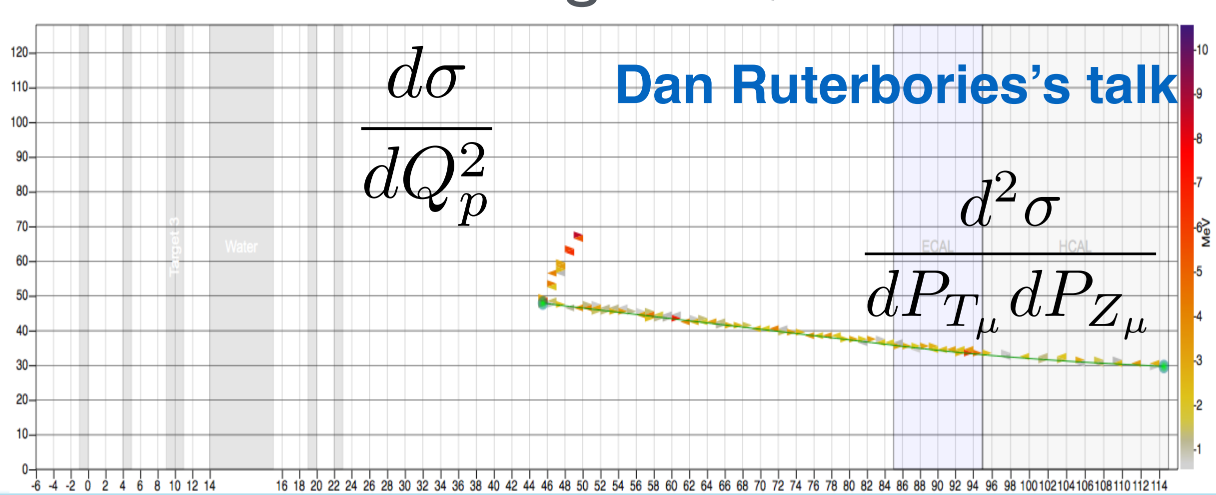
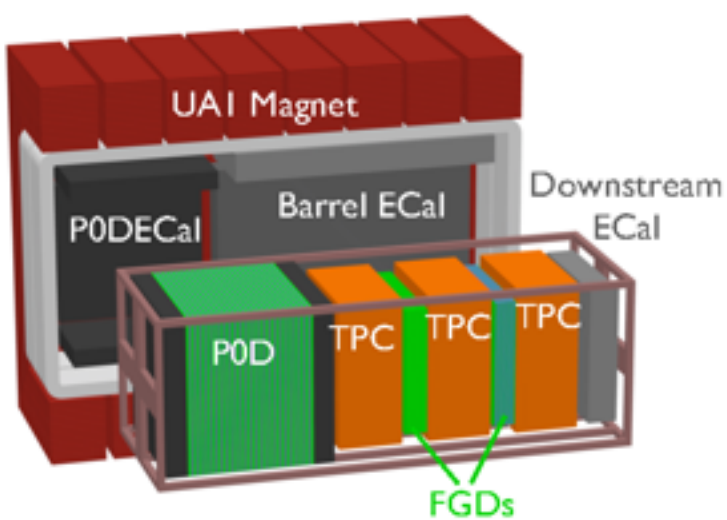


Why We Need to Understand Nuclear Effects?

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- 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 and water measurements even though the far detector is made of water

T2K Near Detector

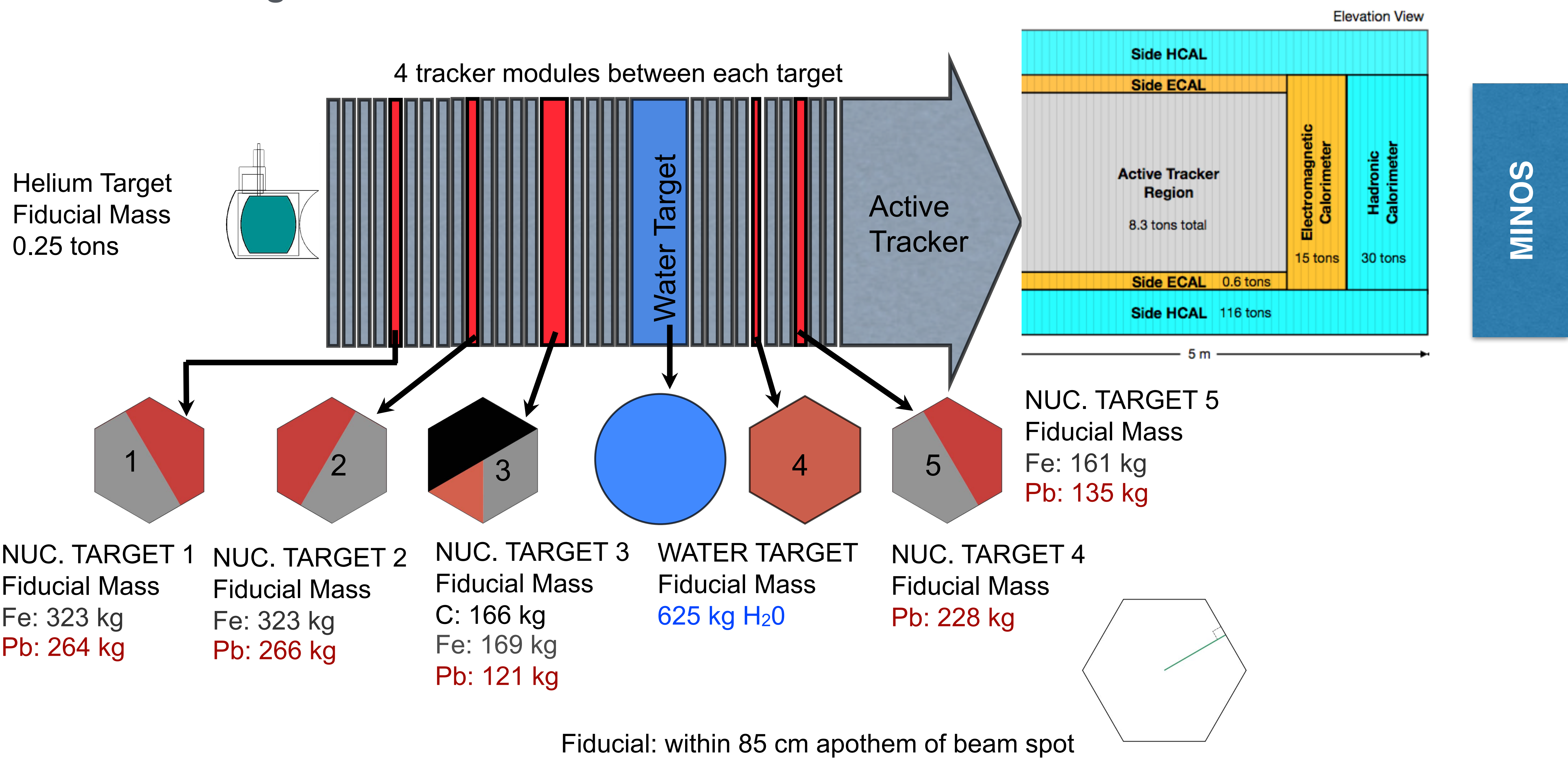


T2K Far Detector

- DUNE near detector final design might include a target different than the far detector?
  - LAr TPC+scintillator?

Studying Nuclear Effects in MINERvA

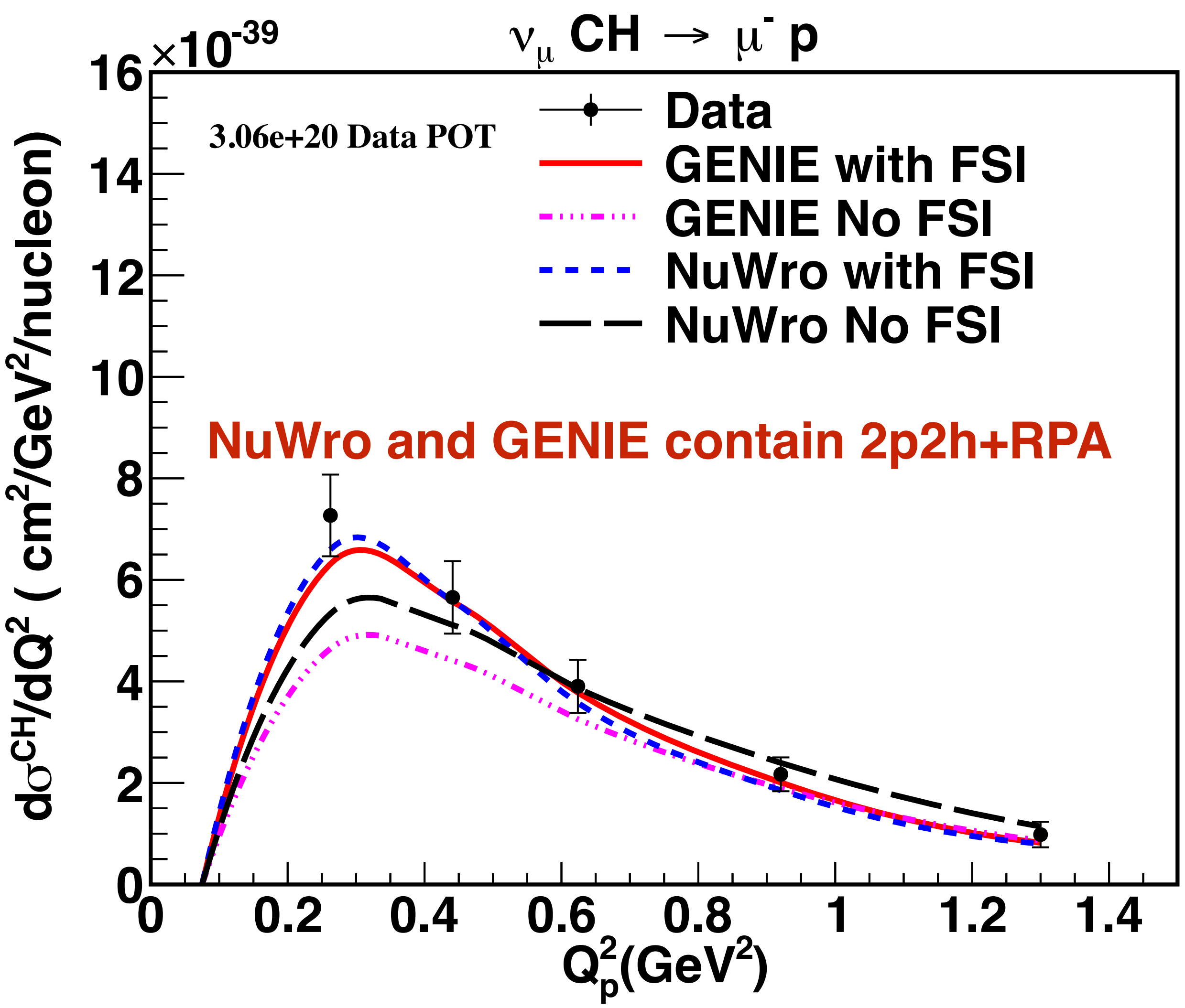
- Different targets built with combinations of different materials



Carbon Iron Lead CH

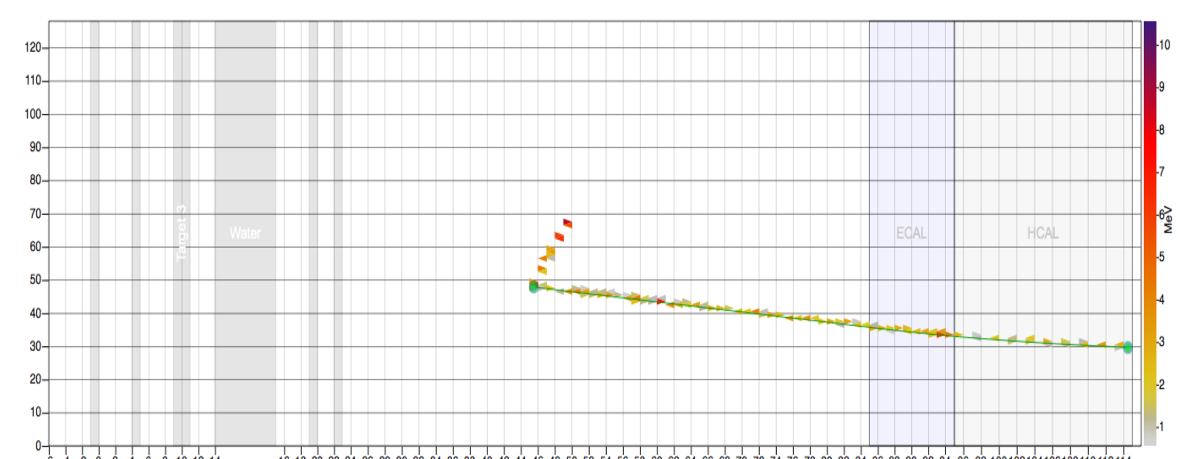
Quasi-Elastic Scattering using the Proton Kinematics

- 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
- At least one proton above 450 MeV



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

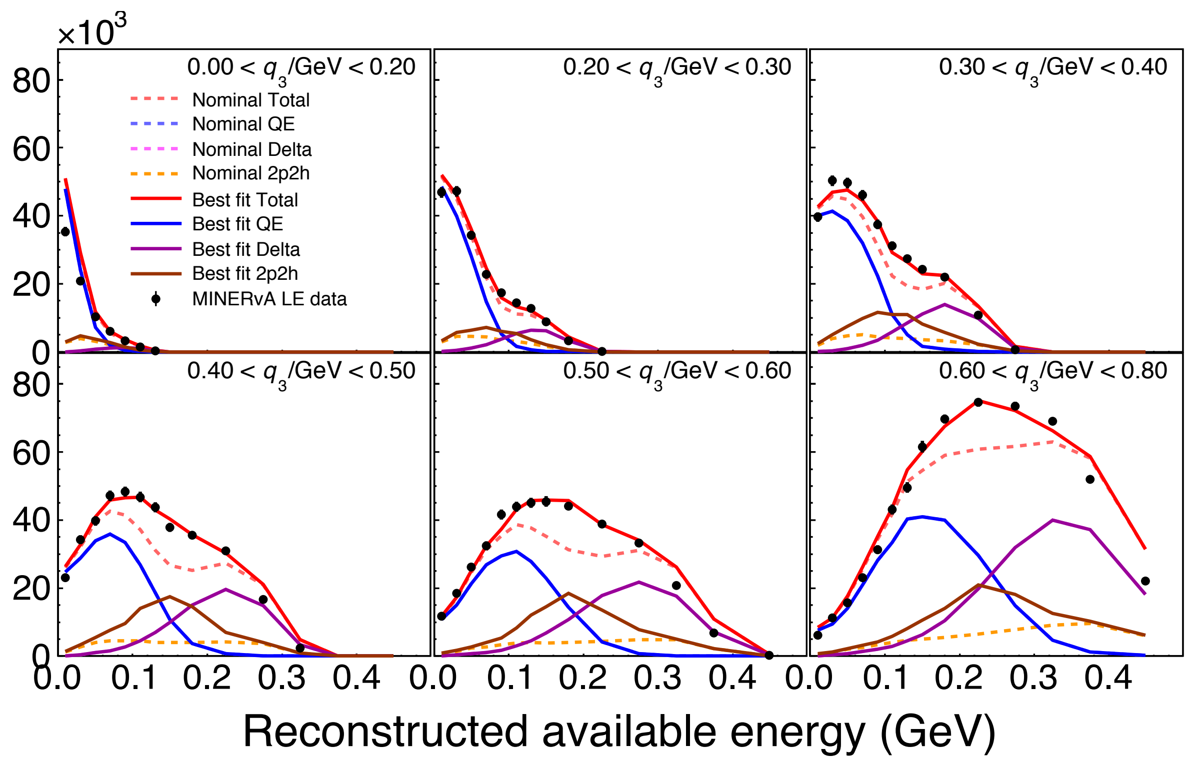
- $M' = M_n - E_b$
- E_b is the binding energy
- T_p is the proton kinetic energy
- M_n is the mass of the neutron
- M_p is the mass of the proton



Updated measurement with latest flux prediction and compared to the latest simulation

Simulations

- We have made considerable progress in modeling neutrino interactions lately, thanks to GENIE collaboration!
- We use GENIE (2.8.4) Monte Carlo generator
- We are using one of the theoretical predictions and latest GENIE implementation of Valencia model for QE-like 2p2h, arXiv:1601.02038, PRC 83, 045501 (2011)

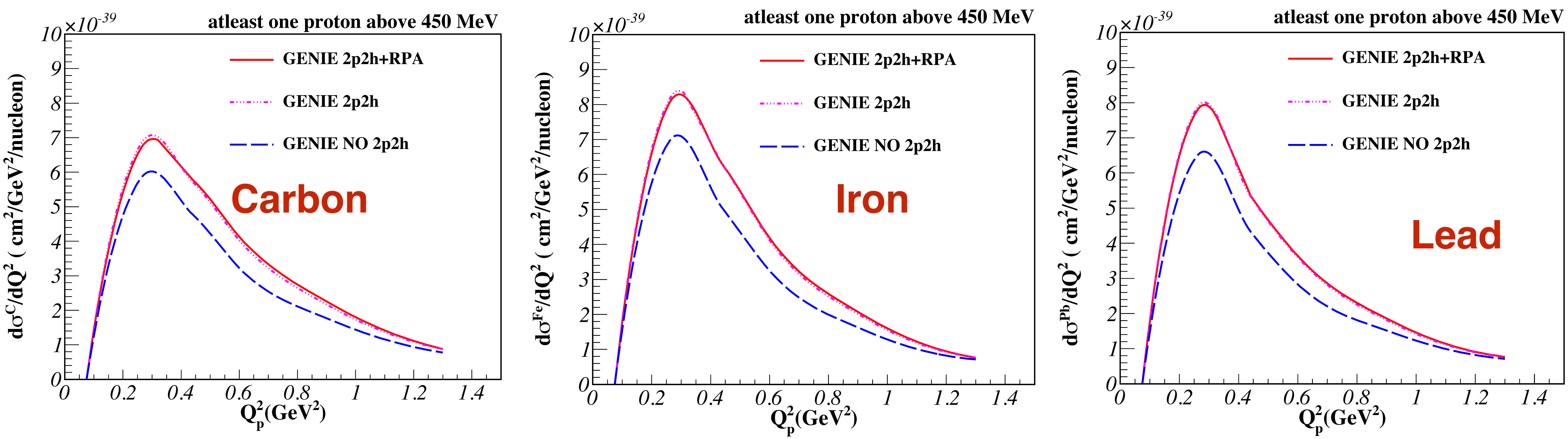


- We use a 2d Gaussian in true variables (q_3,q_0) as a reweighting function applied to the 2p2h events, and fits its parameters to get the best agreement between data and MC (QE and RES are unchanged)

- We add the Valencia RPA to GENIE by reweighting the QE events, Valverde, Amaro, Nieves PLB 638 (2006) 325
- 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

Effect of 2p2h and RPA

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

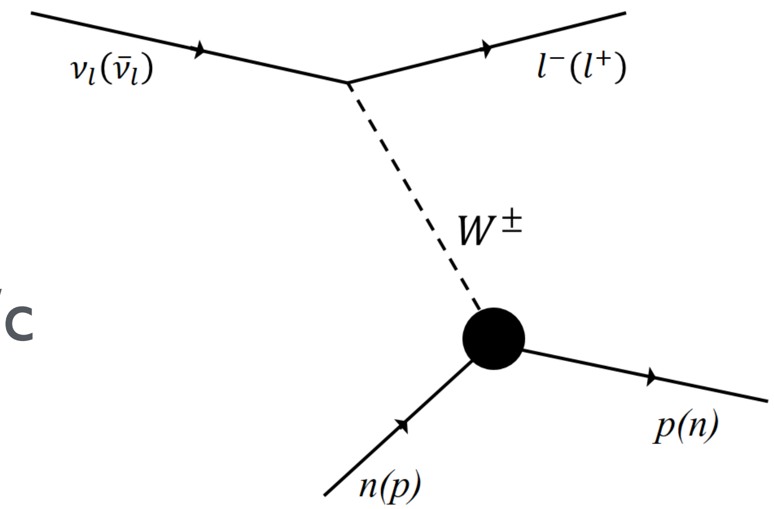


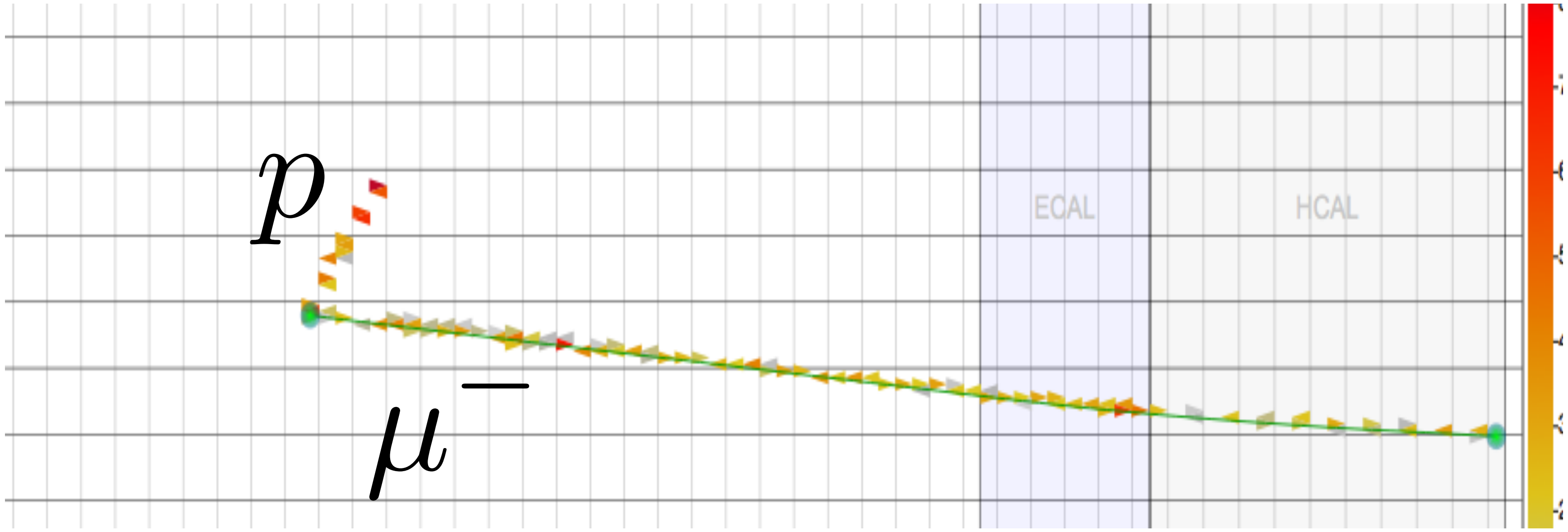
- There is an A dependence in the 2p2h model
- Most of the RPA suppression is below the proton threshold 450 MeV

Analysis

Signal (CCQE-Like)

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





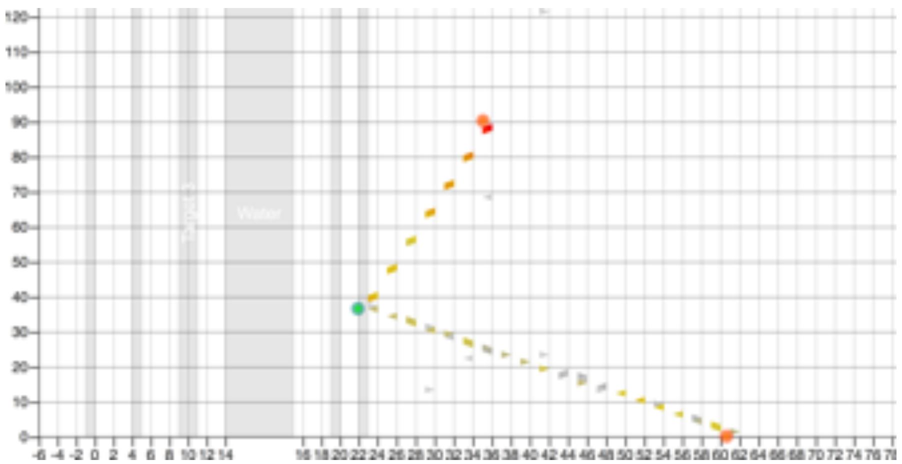
Event Selection Overview

- 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

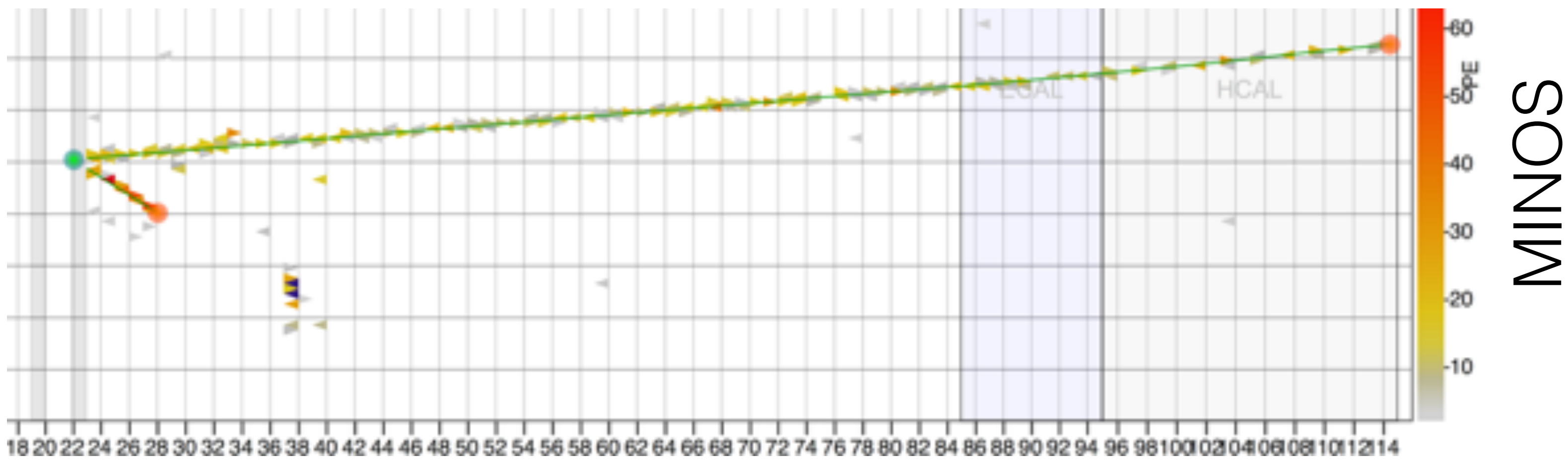
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^{-} \rightarrow e^{-}\bar{\nu_e}\nu_{\mu} \\ \mu^{+} \rightarrow e^{+}\nu_e\bar{\nu_{\mu}} \end{array}$$

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

Analysis includes events with muons that exit the sides of MINERvA

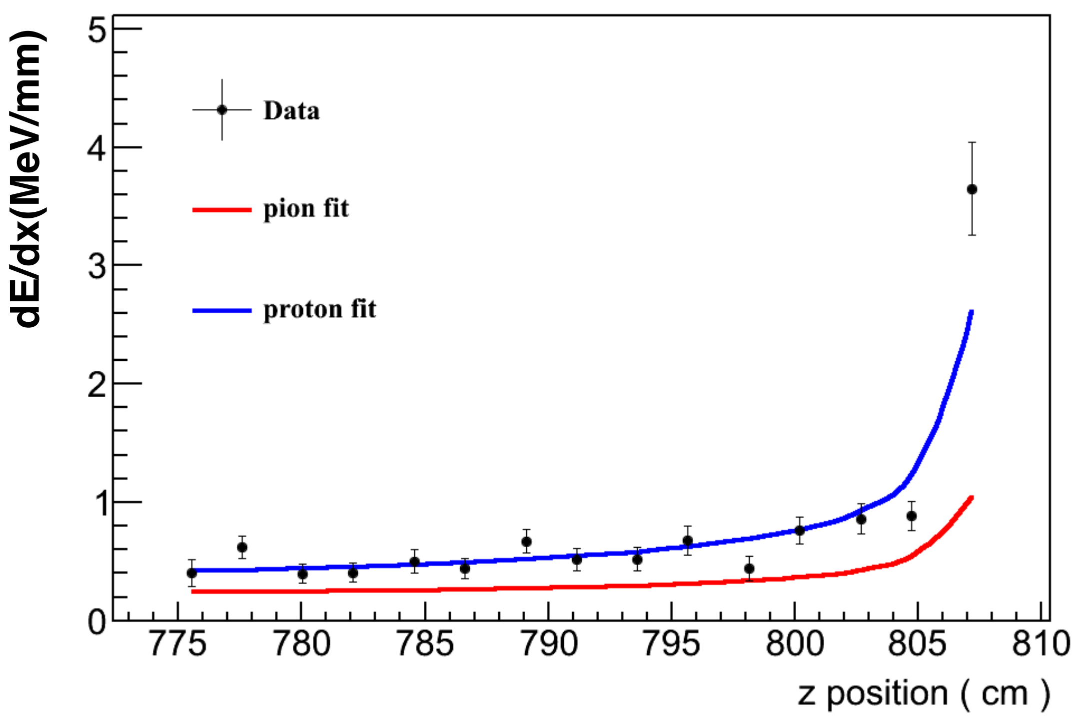


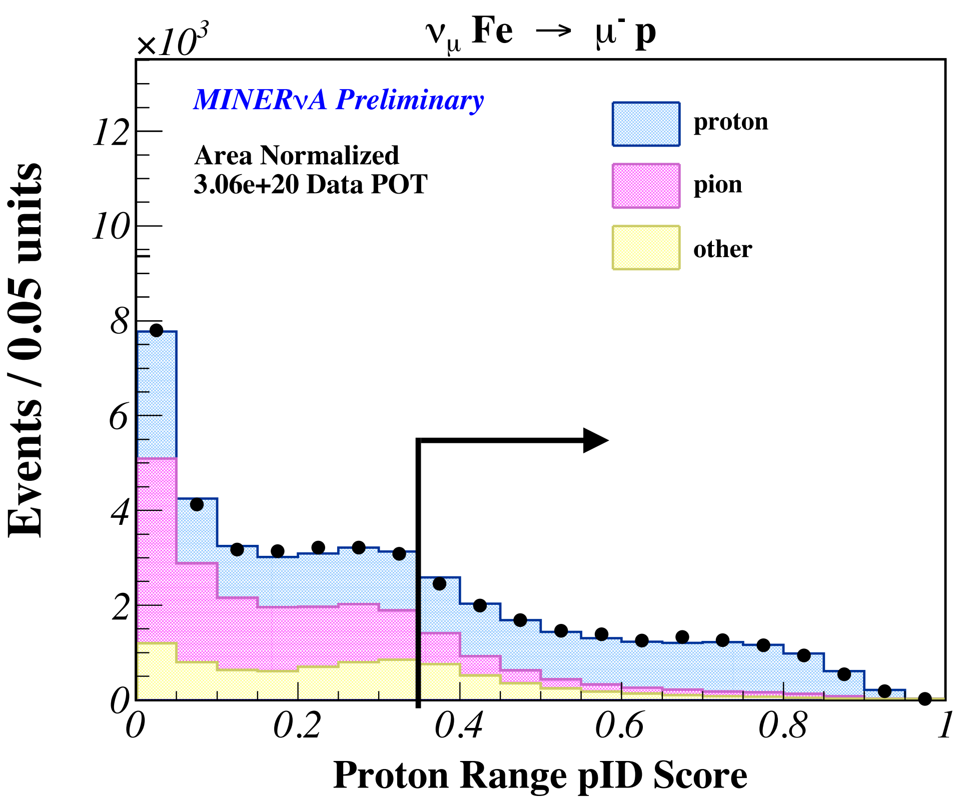
Analysis includes events with muons matched to MINOS



Selecting Events with Protons (Proton pID Score Cut)

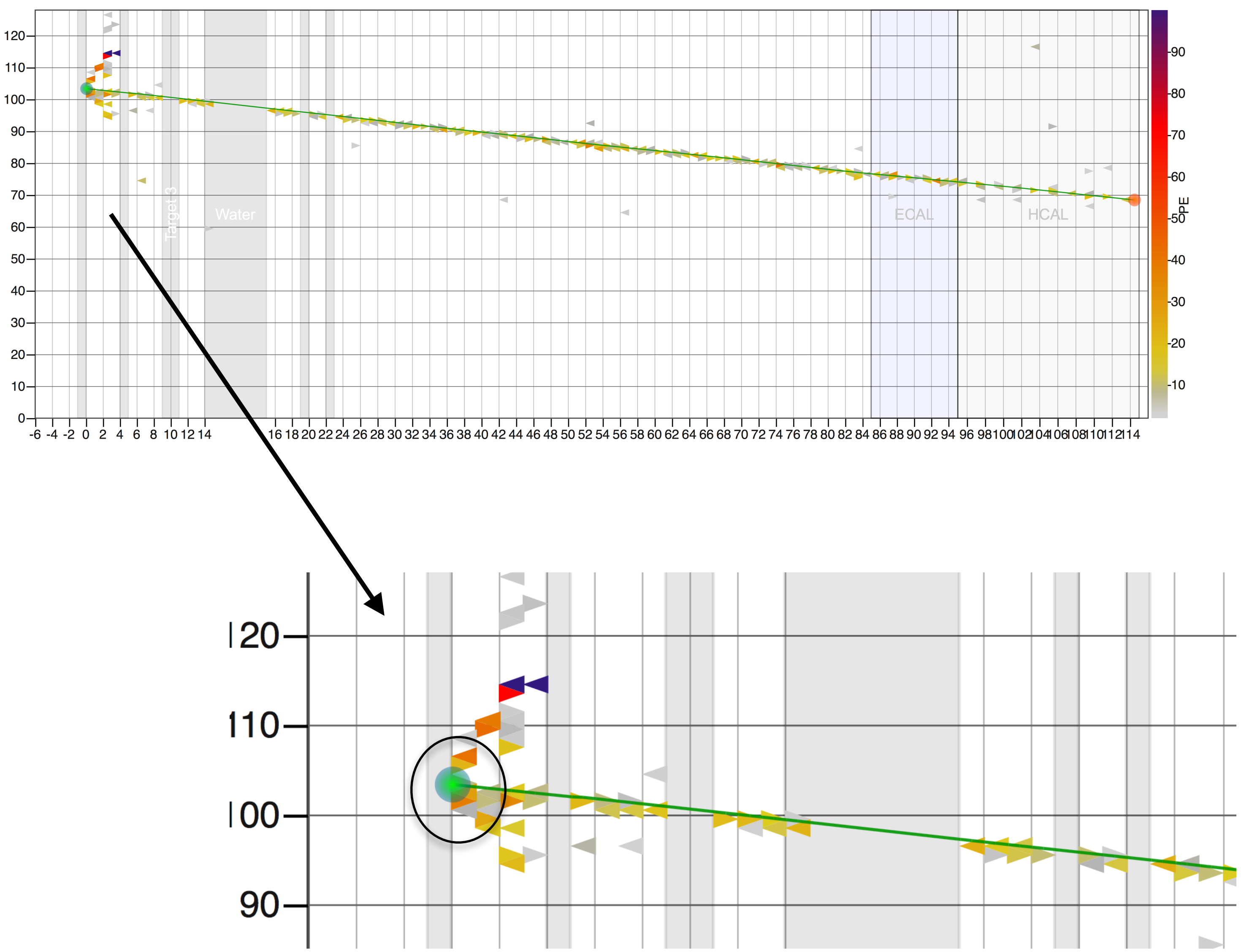
- Require events with a proton candidate
  - Fit each hadron track energy loss dE/dx profile to both pion and proton loss profile for particle identification
  - Use the χ^2/dof values from pion and proton fits to create a score and select the proton candidate

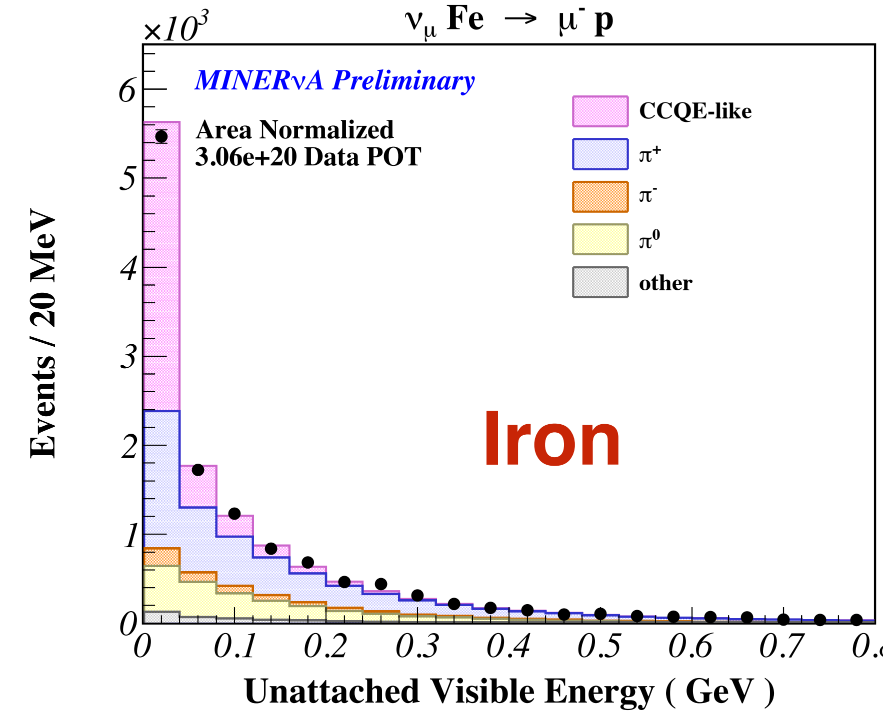


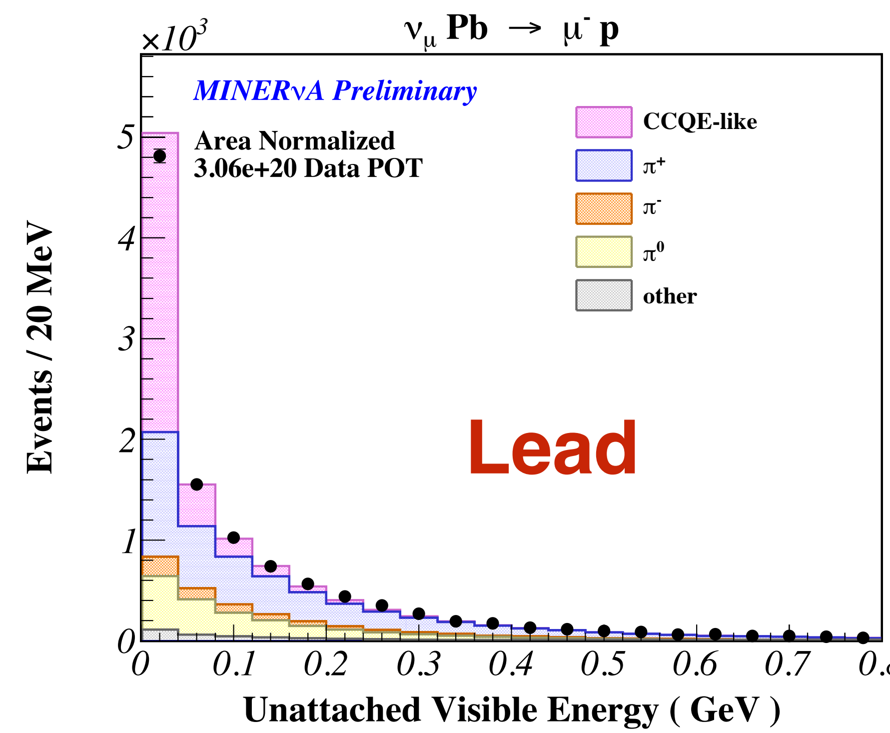


Removing Background Events

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



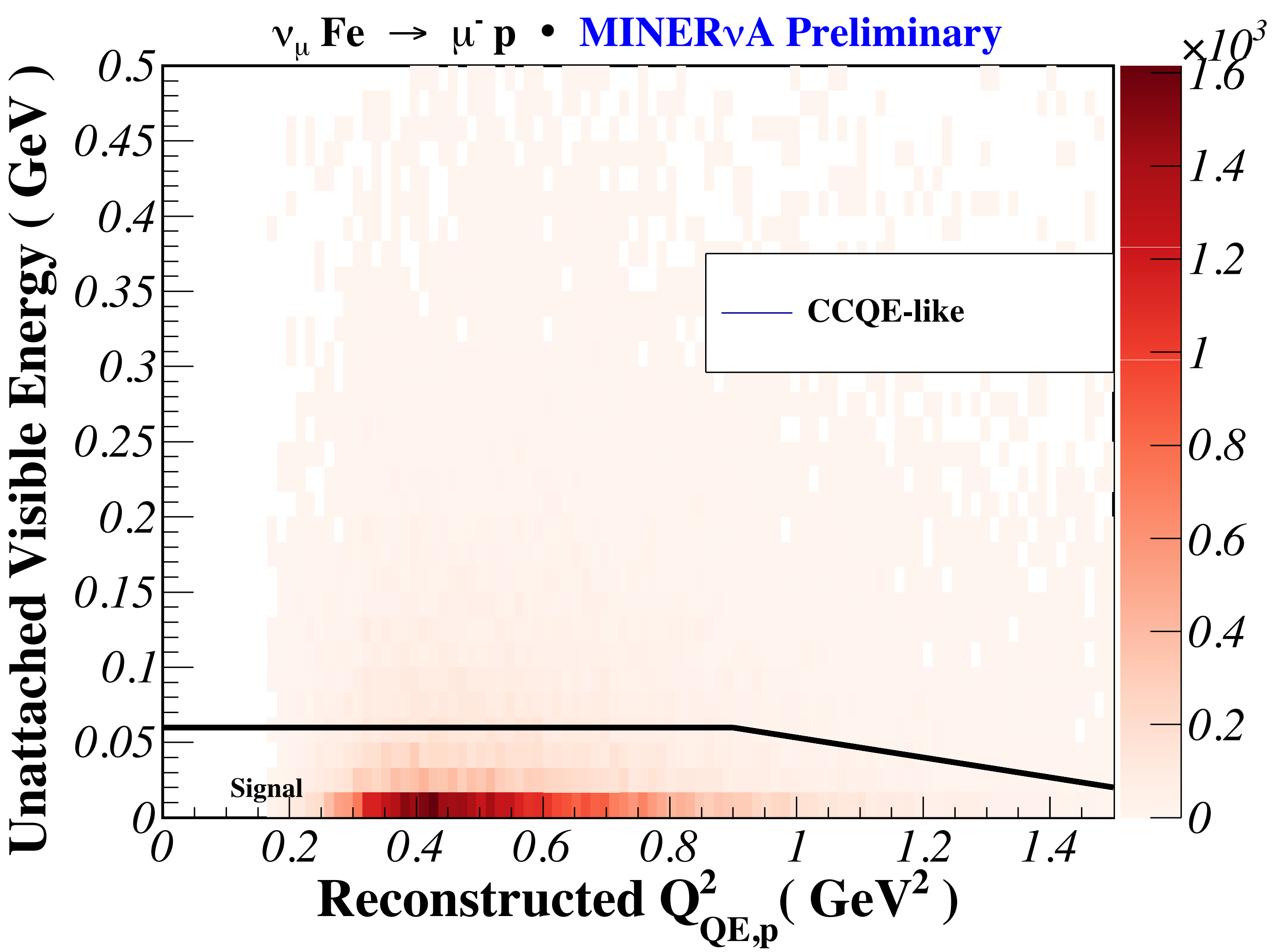


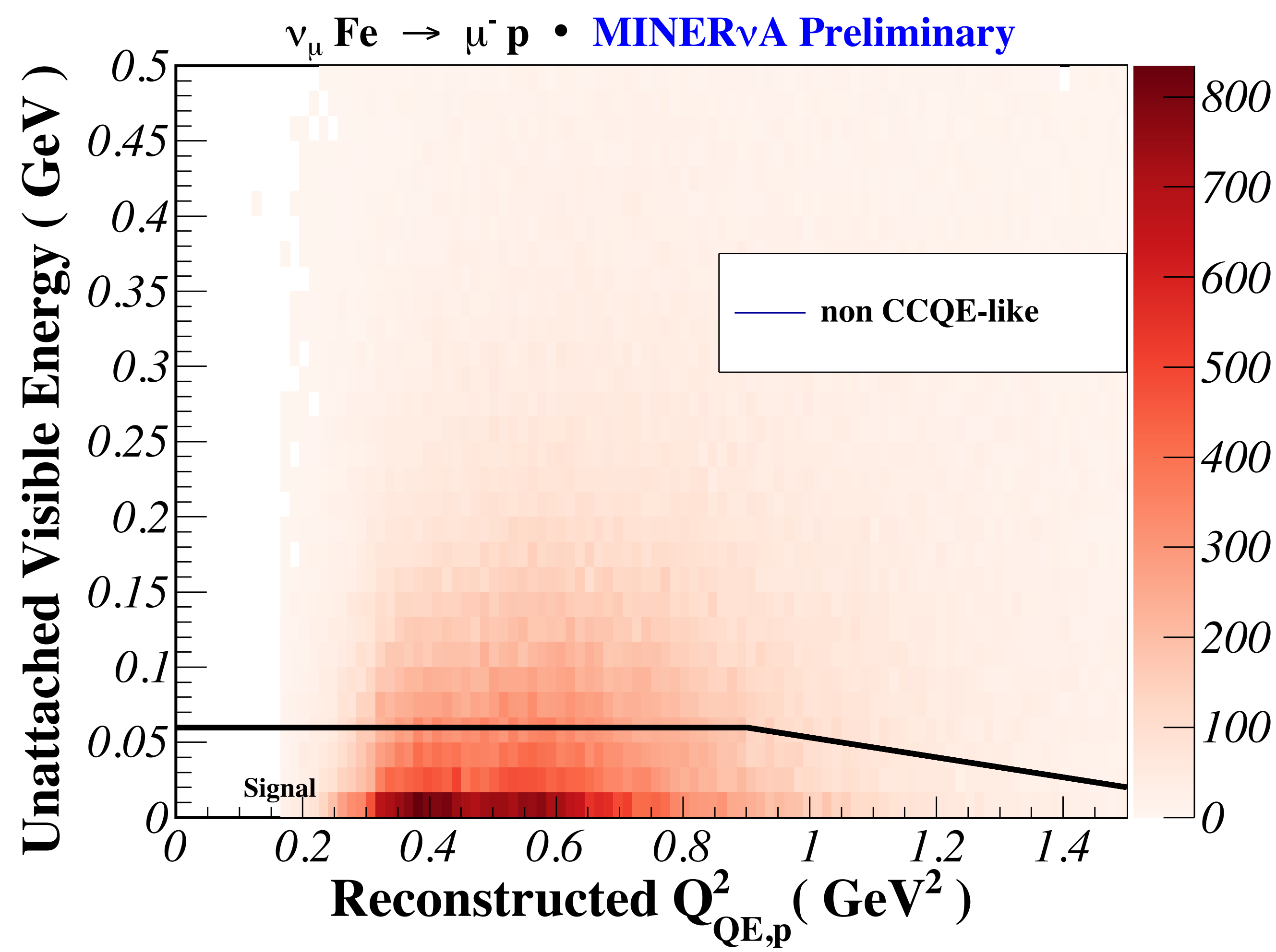


Unattached Visible Energy vs Q^2 Cut

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

Iron

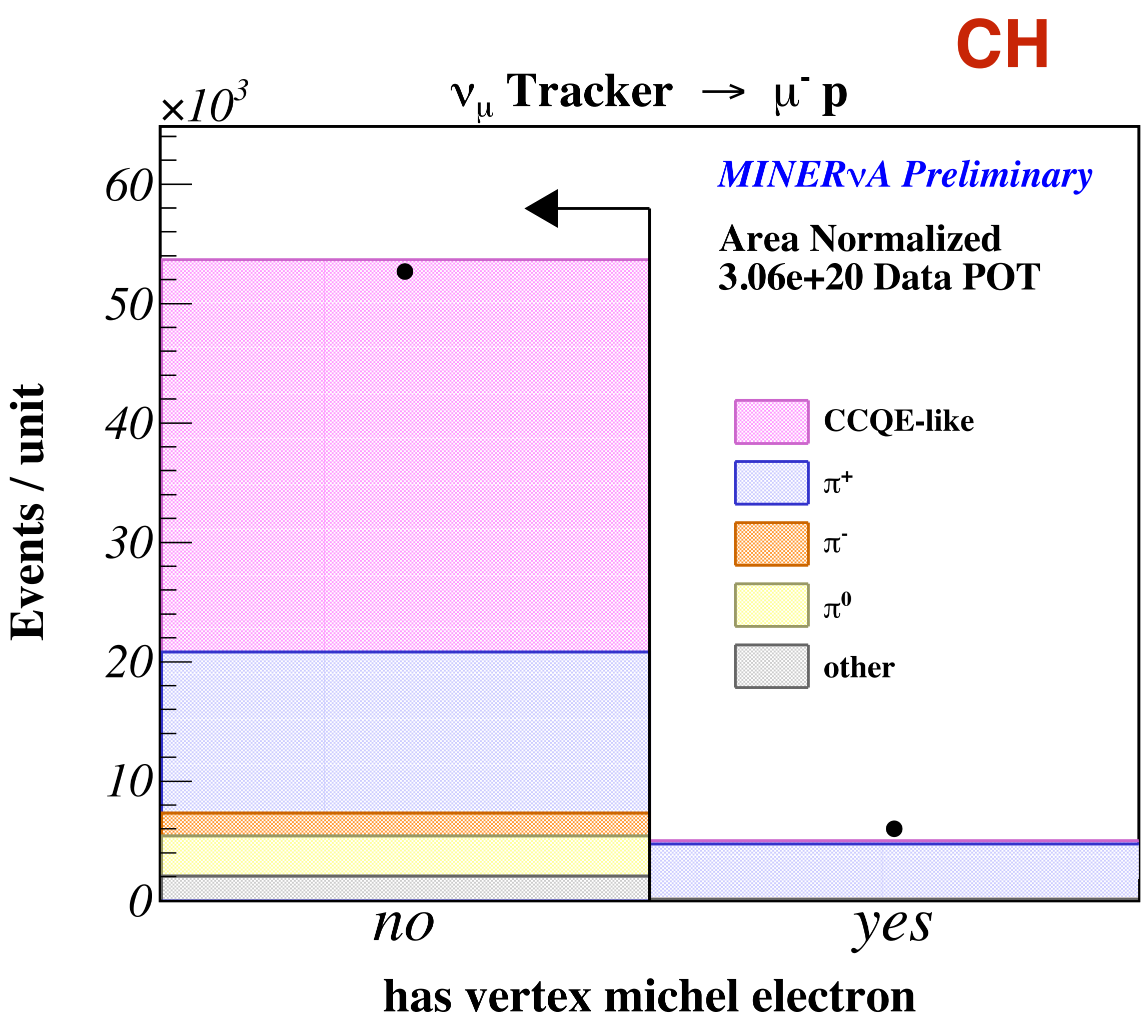


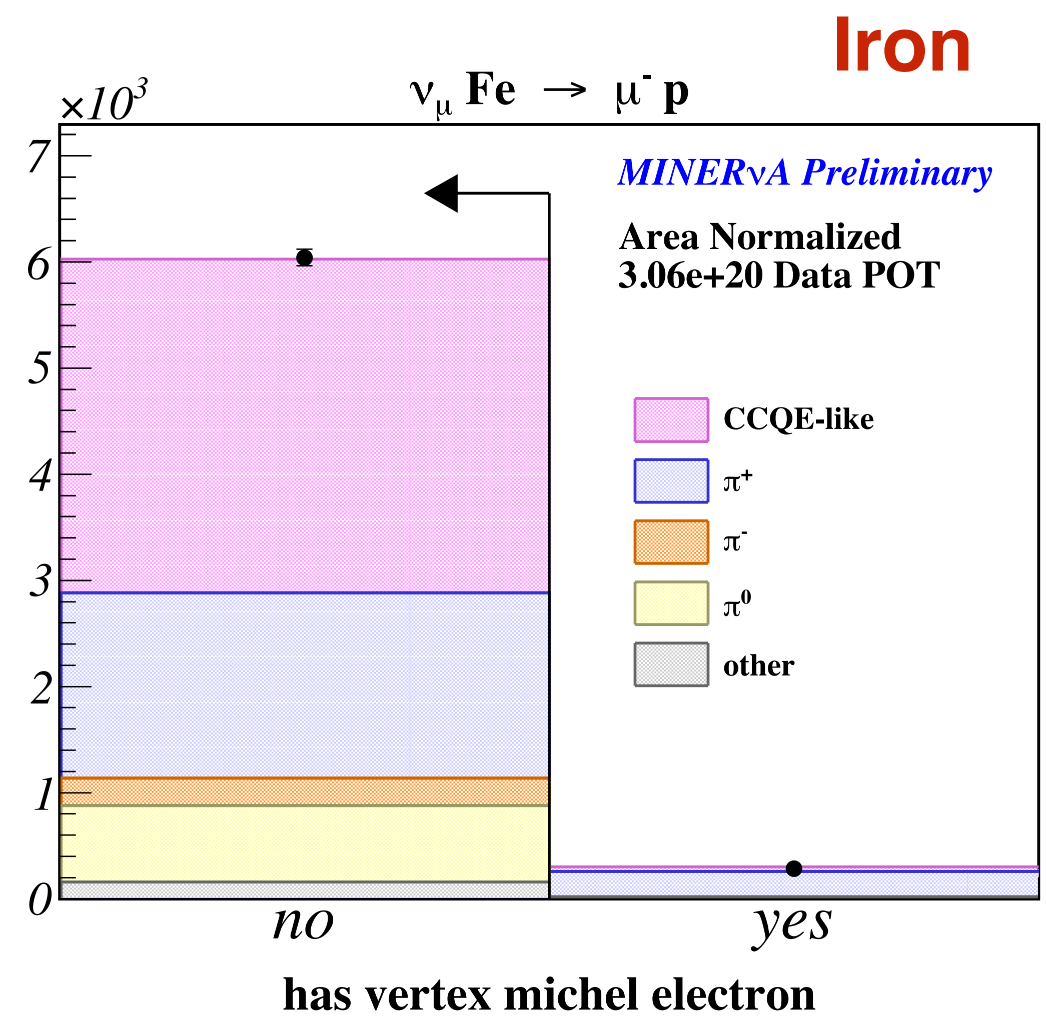


Michel Veto

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

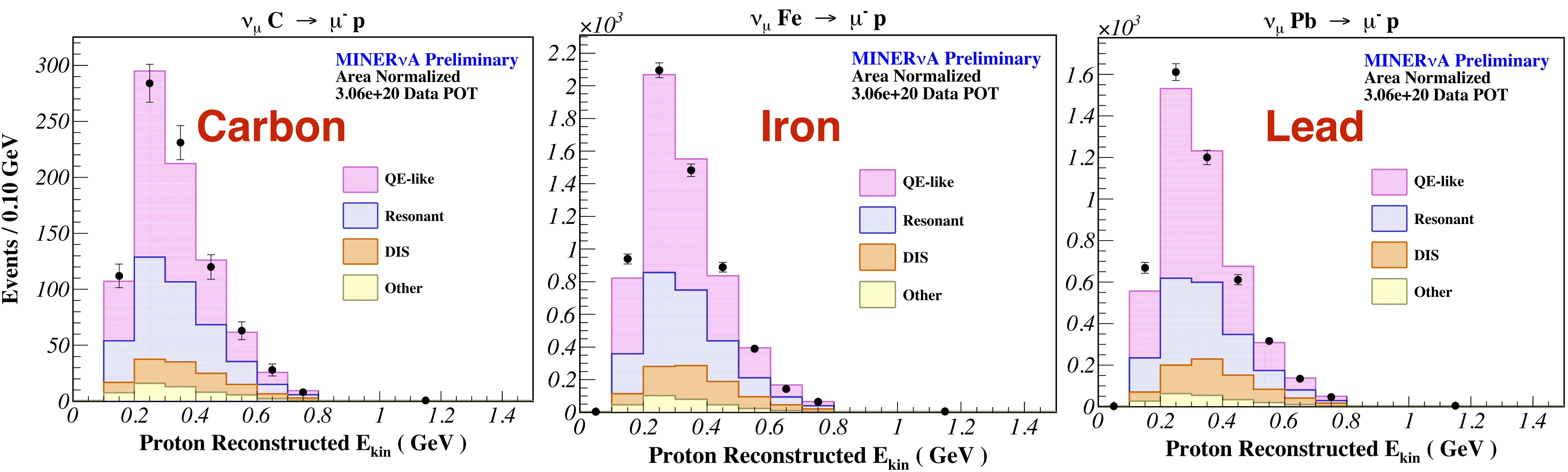
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^{-} \rightarrow e^{-}\bar{\nu_e}\nu_{\mu} \\ \mu^{+} \rightarrow e^{+}\nu_e\bar{\nu_{\mu}} \end{array}$$





Selected Sample

- Events passing the analysis selection cuts

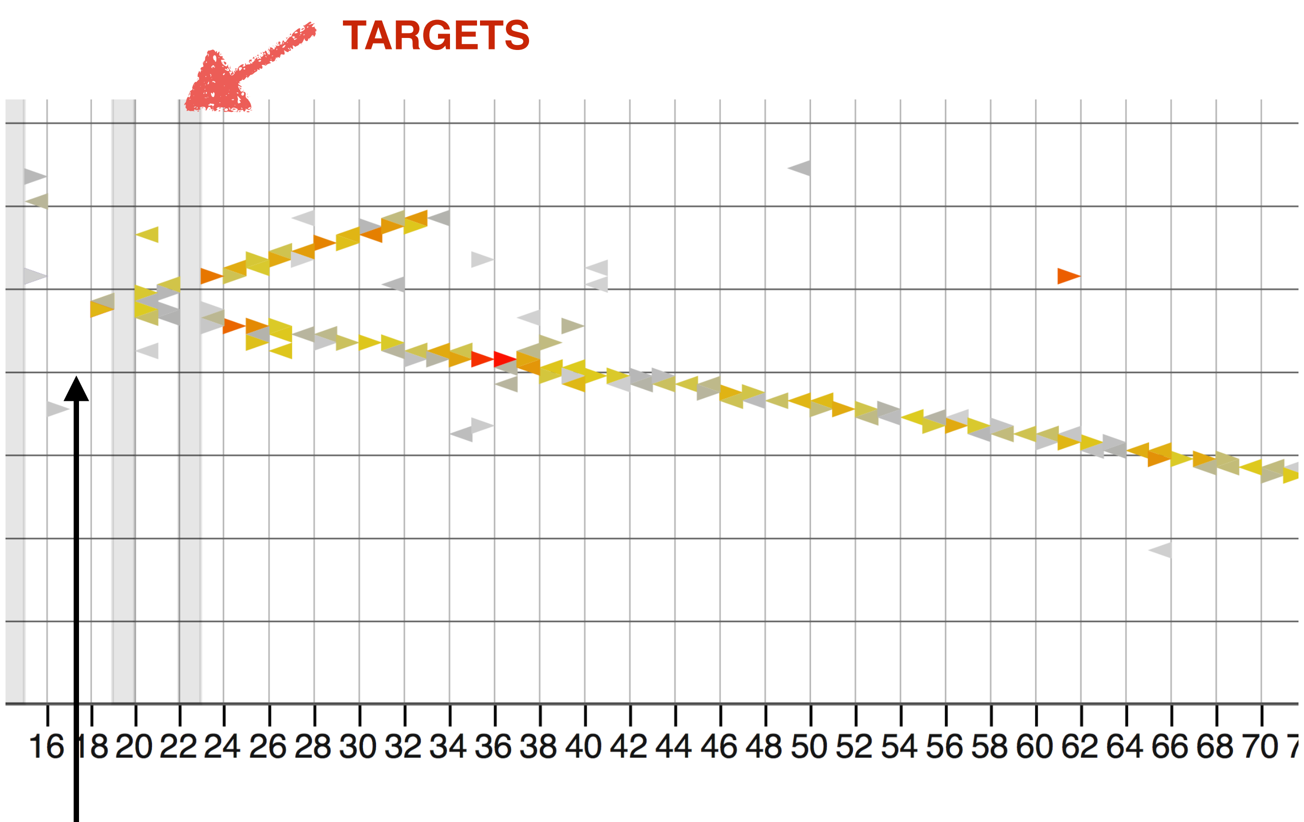


- The dominant background is from resonance events
  - Resonance background events ~30%, deep inelastic background events 10%

Background Constraint Procedure

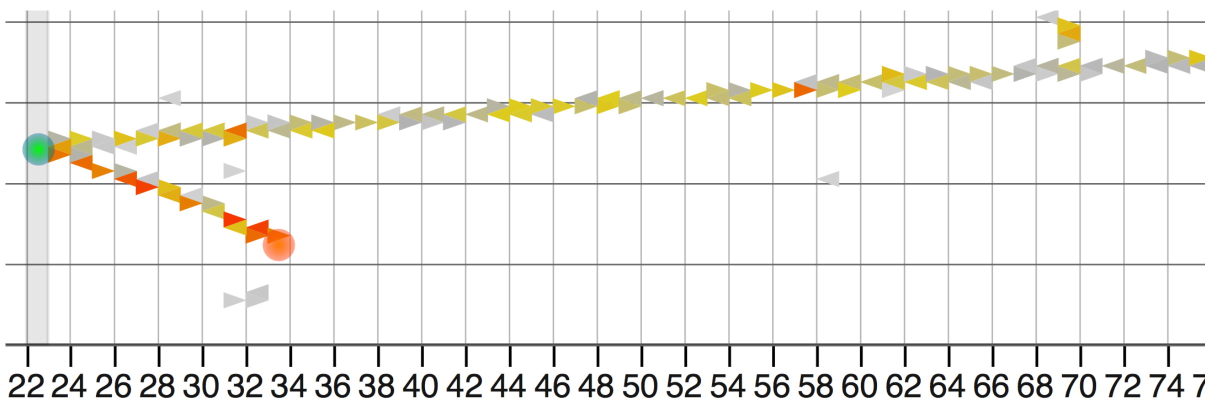
- Backgrounds:
    1. Scintillator background: events that occurred outside the nuclear targets
    2. Non-CCQE like background: where the pions have been misidentified as proton, not removed by cuts

Scintillator background



Interaction outside the target

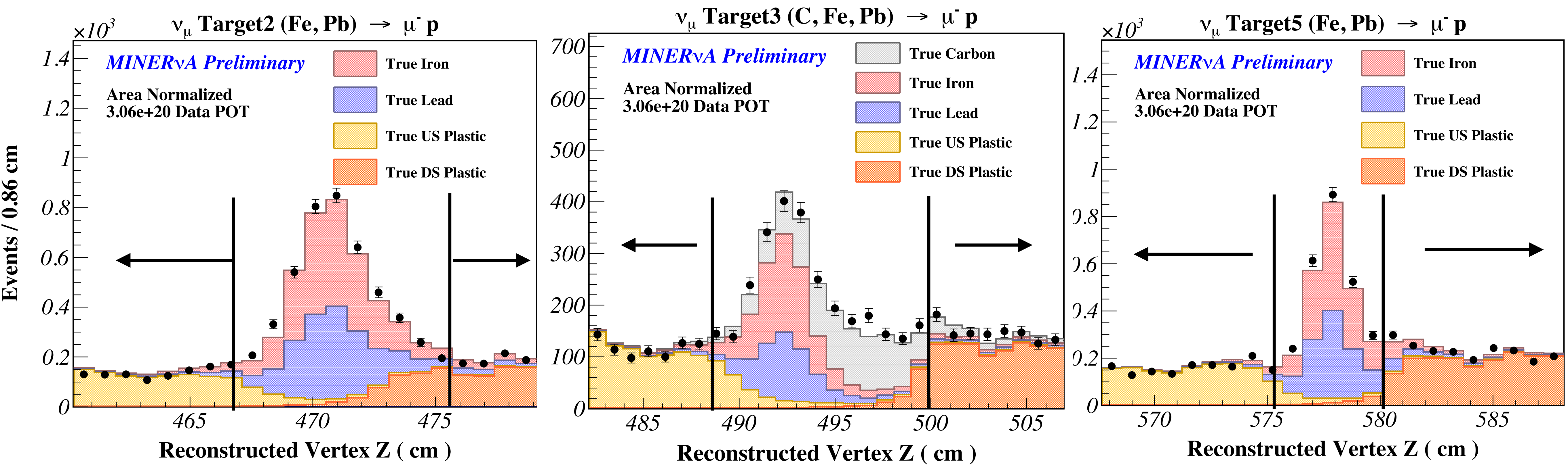
Non-CCQE Background



Inelastic

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



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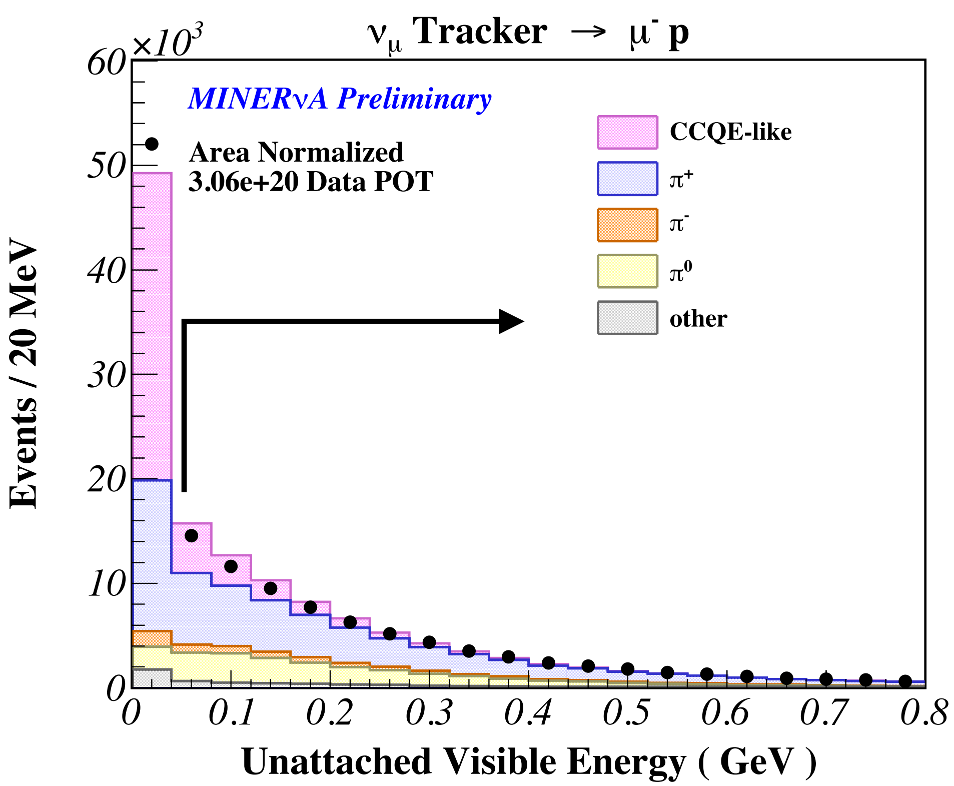
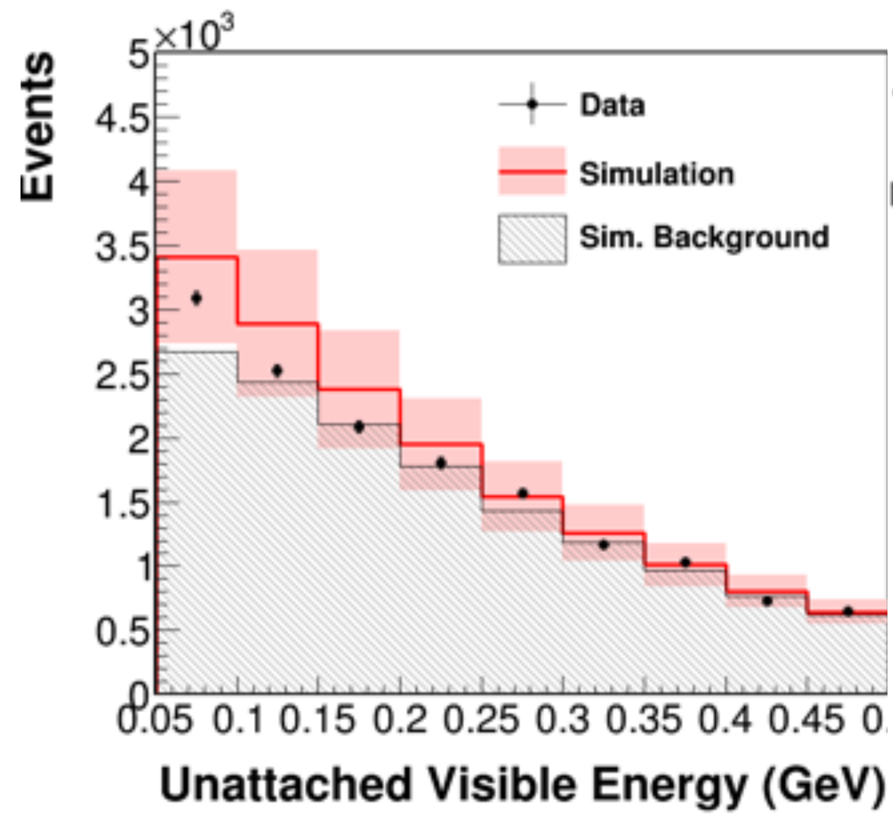
Background Constraint Procedure for Non-CCQE like

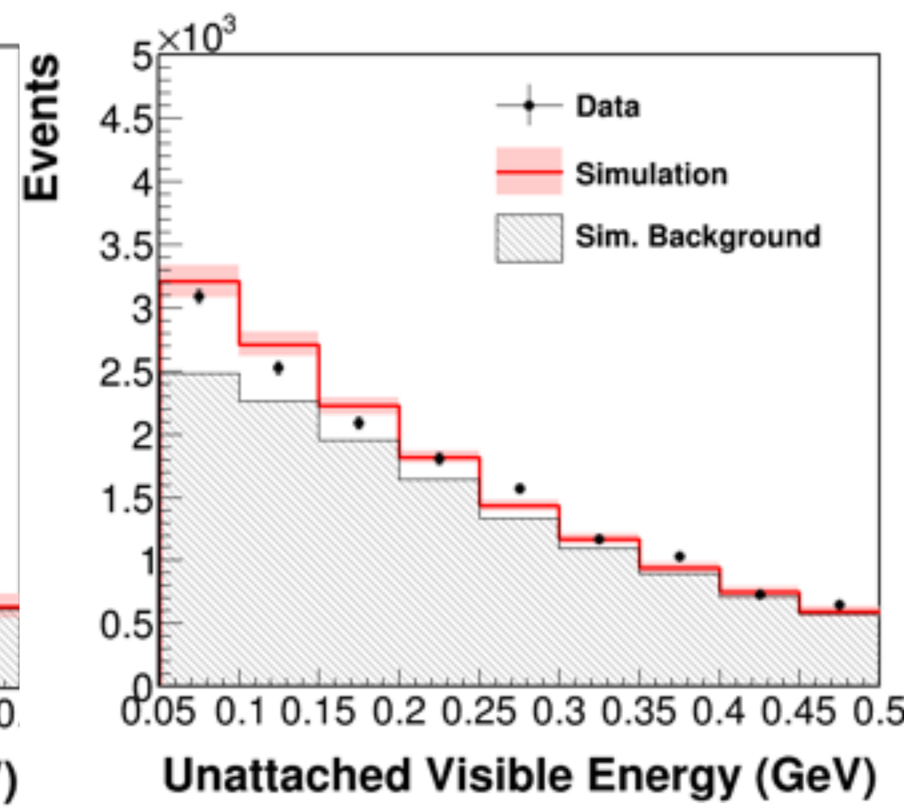
- Using the unattached visible energy for the events passing the proton pID for two different bins of Q^2 in the tracker
- Using the background dominated region in the unattached visible energy distribution
- Let the background float in the fit while keeping the signal constant until the total matches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



Before the constraint



After the constraint



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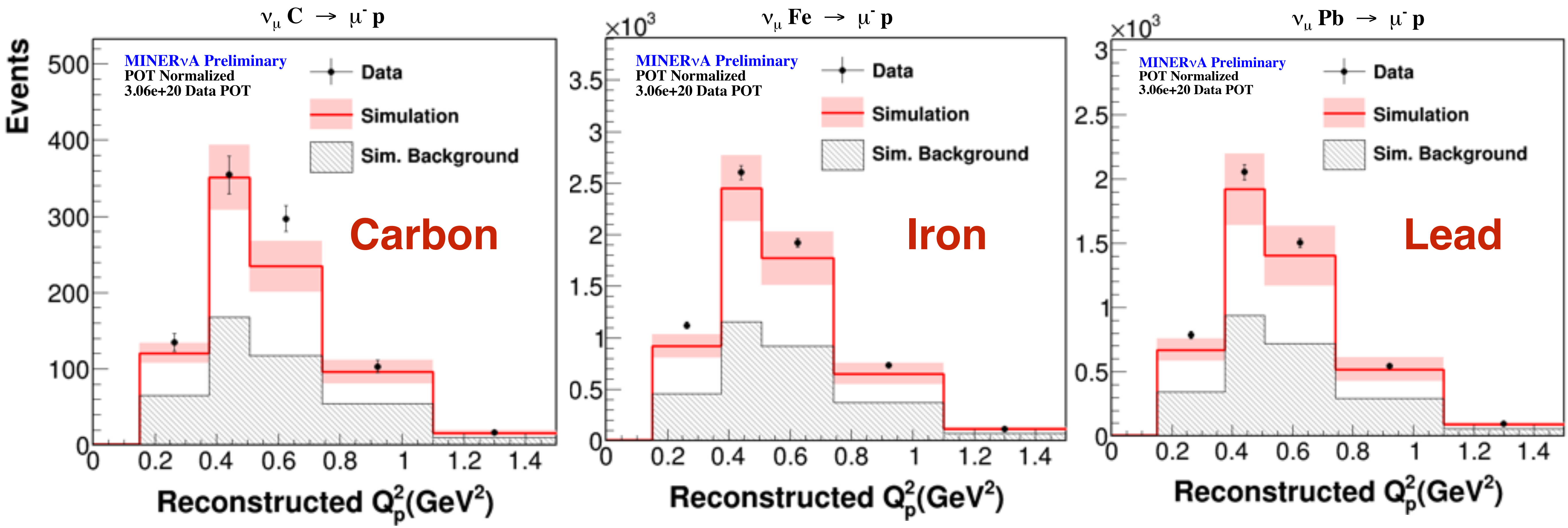
Reconstructed Proton Q^2

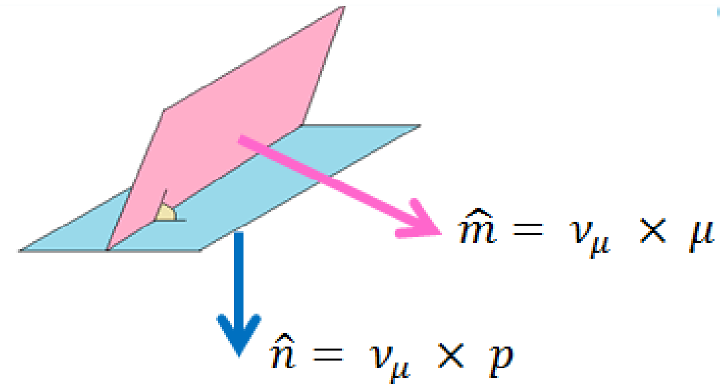
- After all the cuts



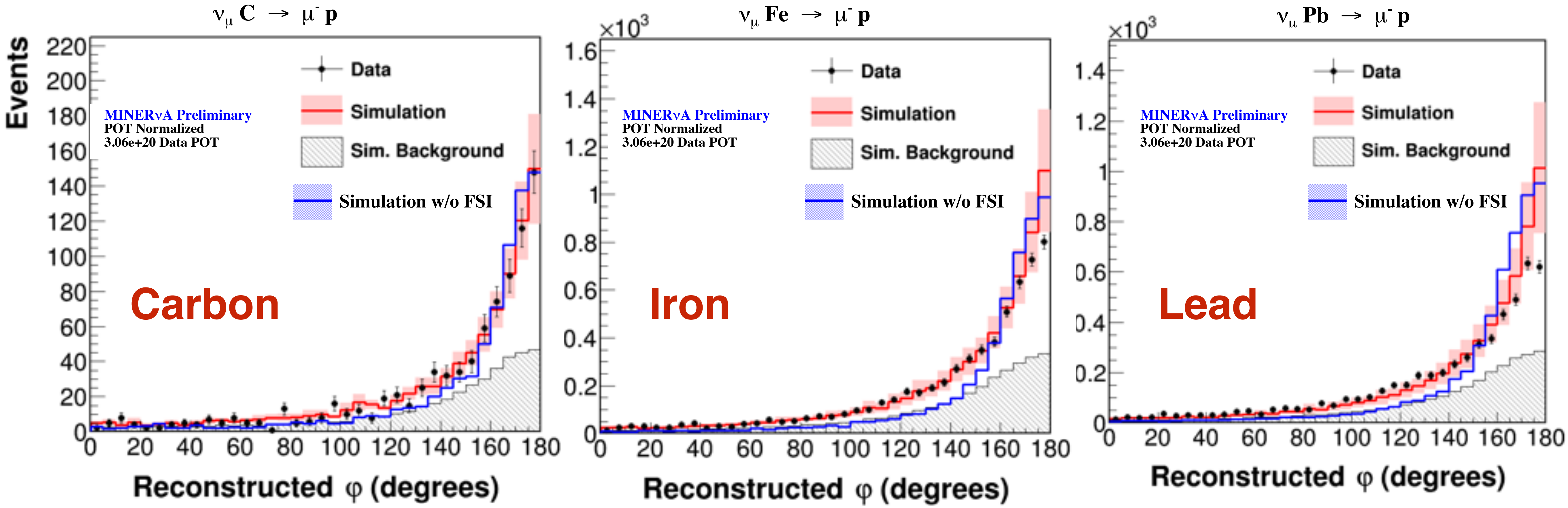
- Background has been tuned
- Distributions contain the background from the scintillator

Coplanarity Angle

- After all the cuts

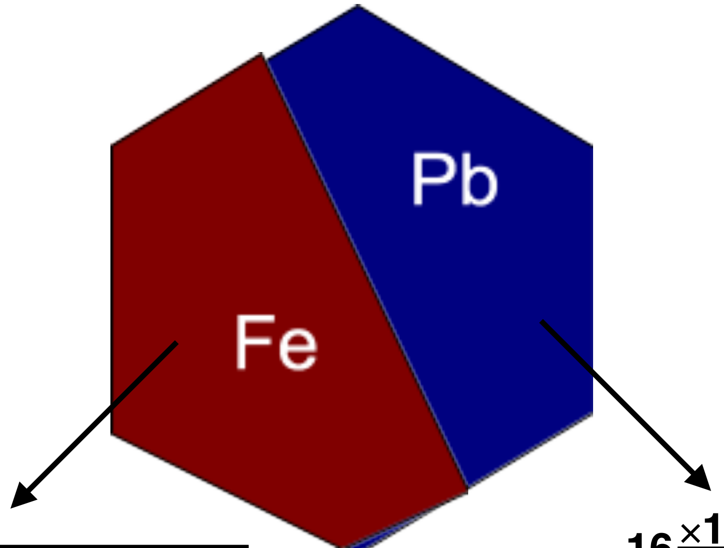


$$\varphi = \cos^{-1}\left(\frac{(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu)\cdot(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p)}{|\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu||\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p|}\right)$$



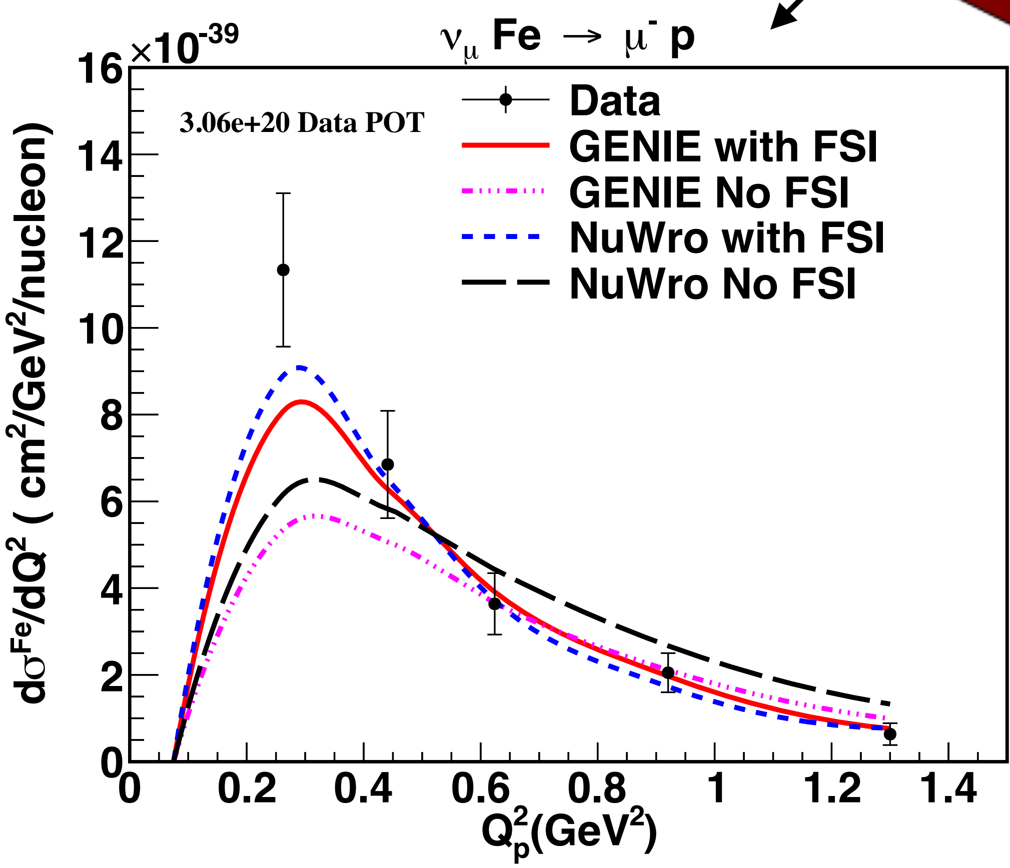
- Background has been tuned
- Data/MC discrepancy increases with A

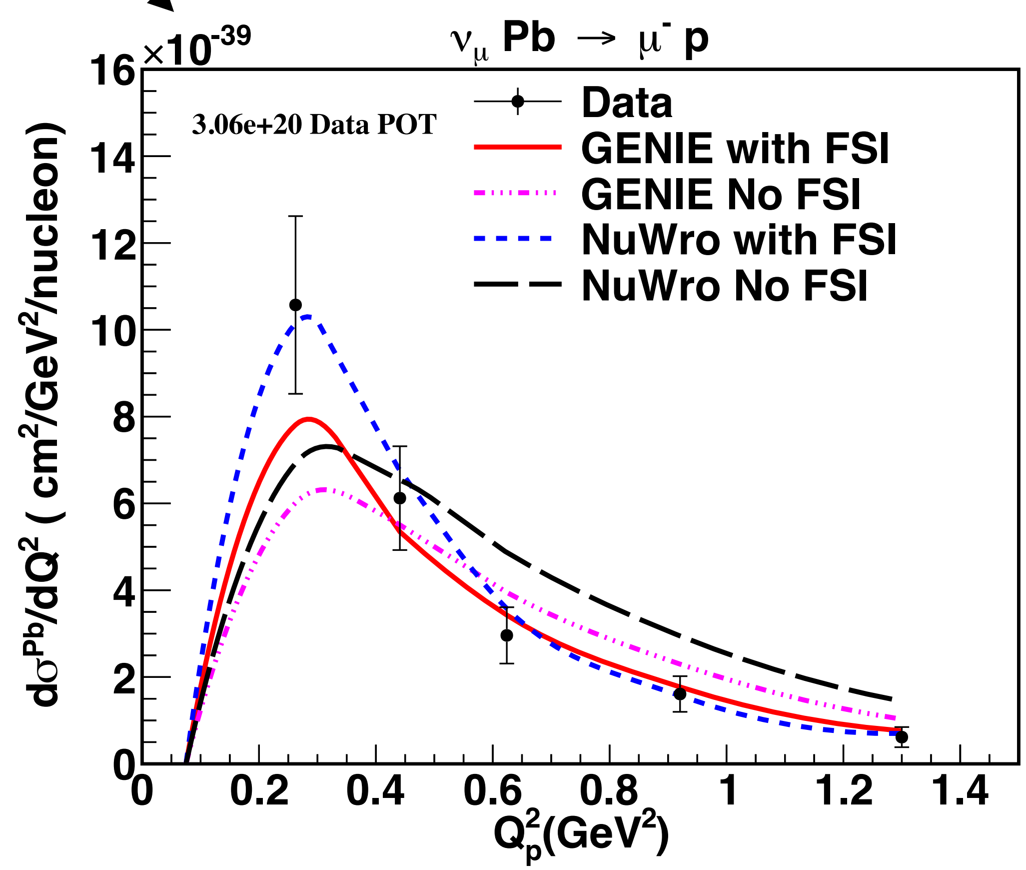
Measurements in Iron and Lead



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





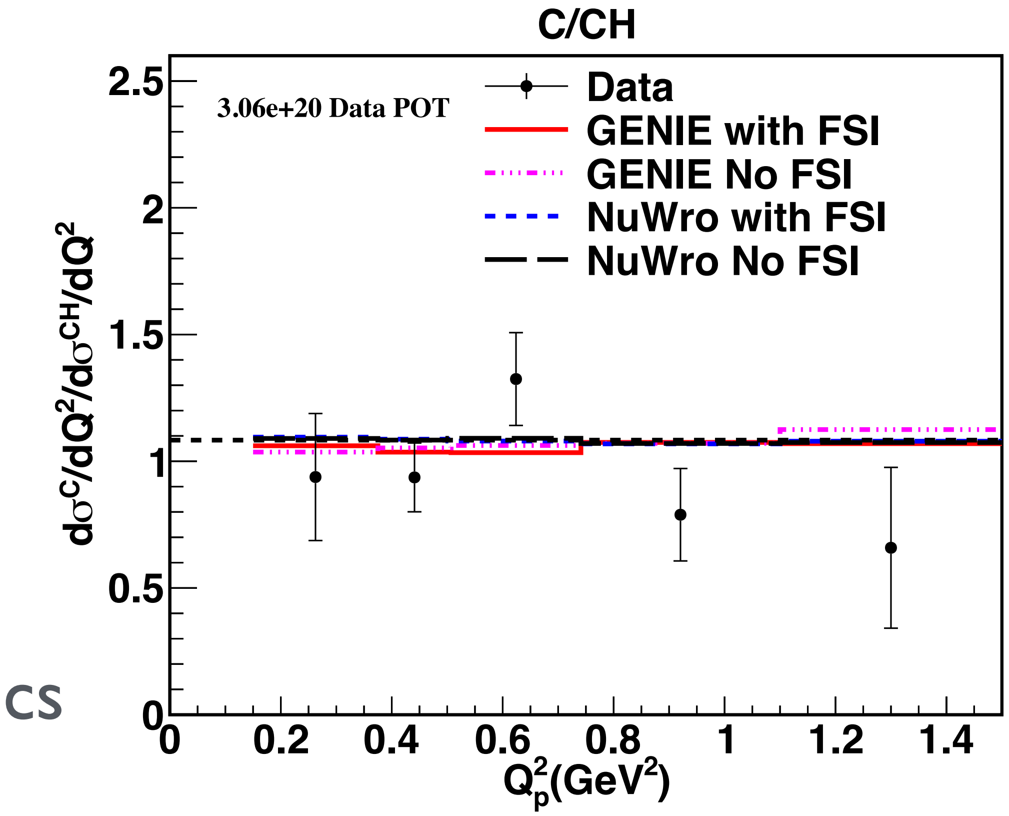
NuWro and GENIE contain 2p2h+RPA

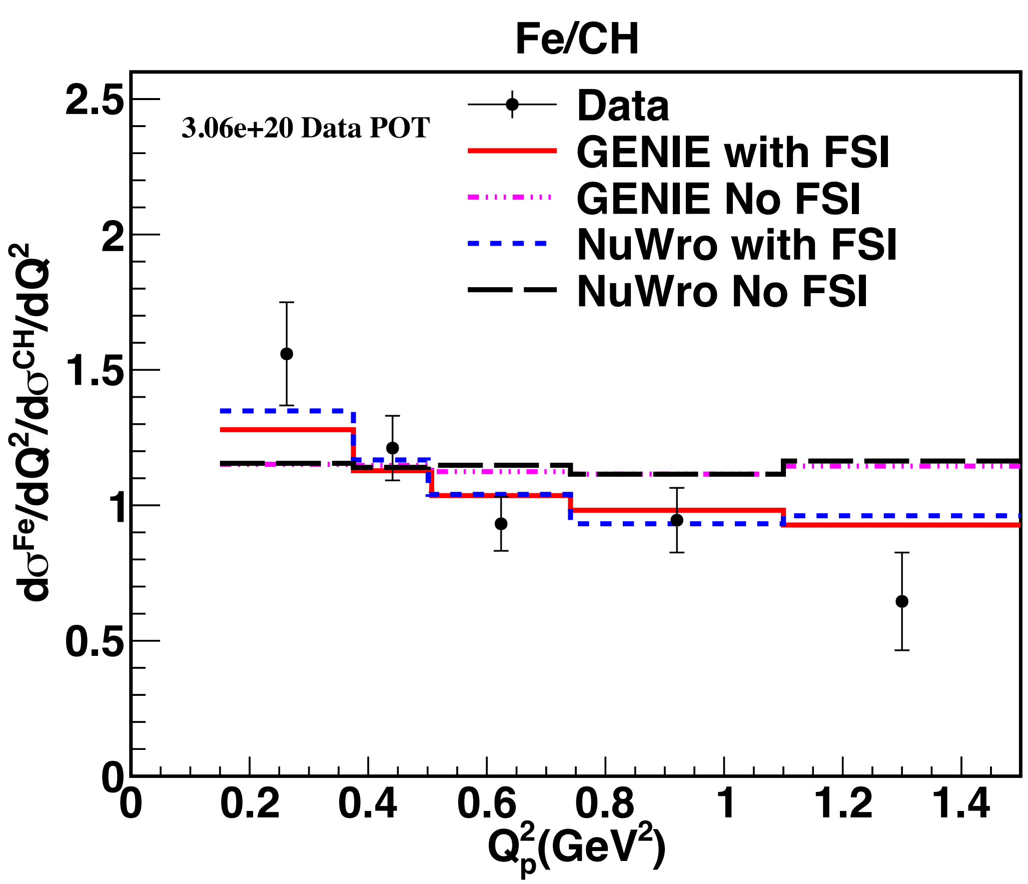
arXiv:1705.03791

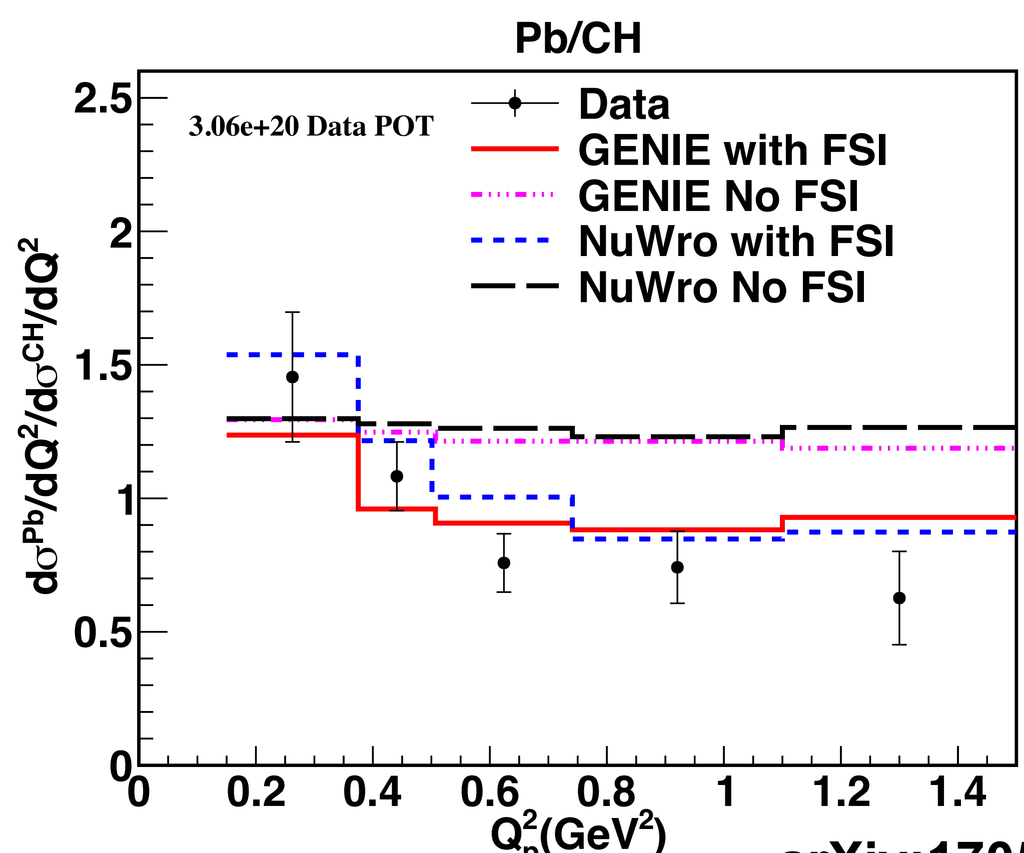
- Lead data favor the A-dependence predicted by the NuWro generator

Ratio Measurements

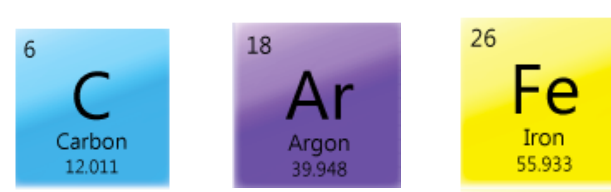
- First CCQE measurement in the nuclear targets Carbon, Iron and Lead to study Q^2 dependence of nuclear effects
- Ratio measurements tell us about nuclear effects mainly from final state interactions
- The data ratios are helped by reduction of systematics uncertainties including the flux





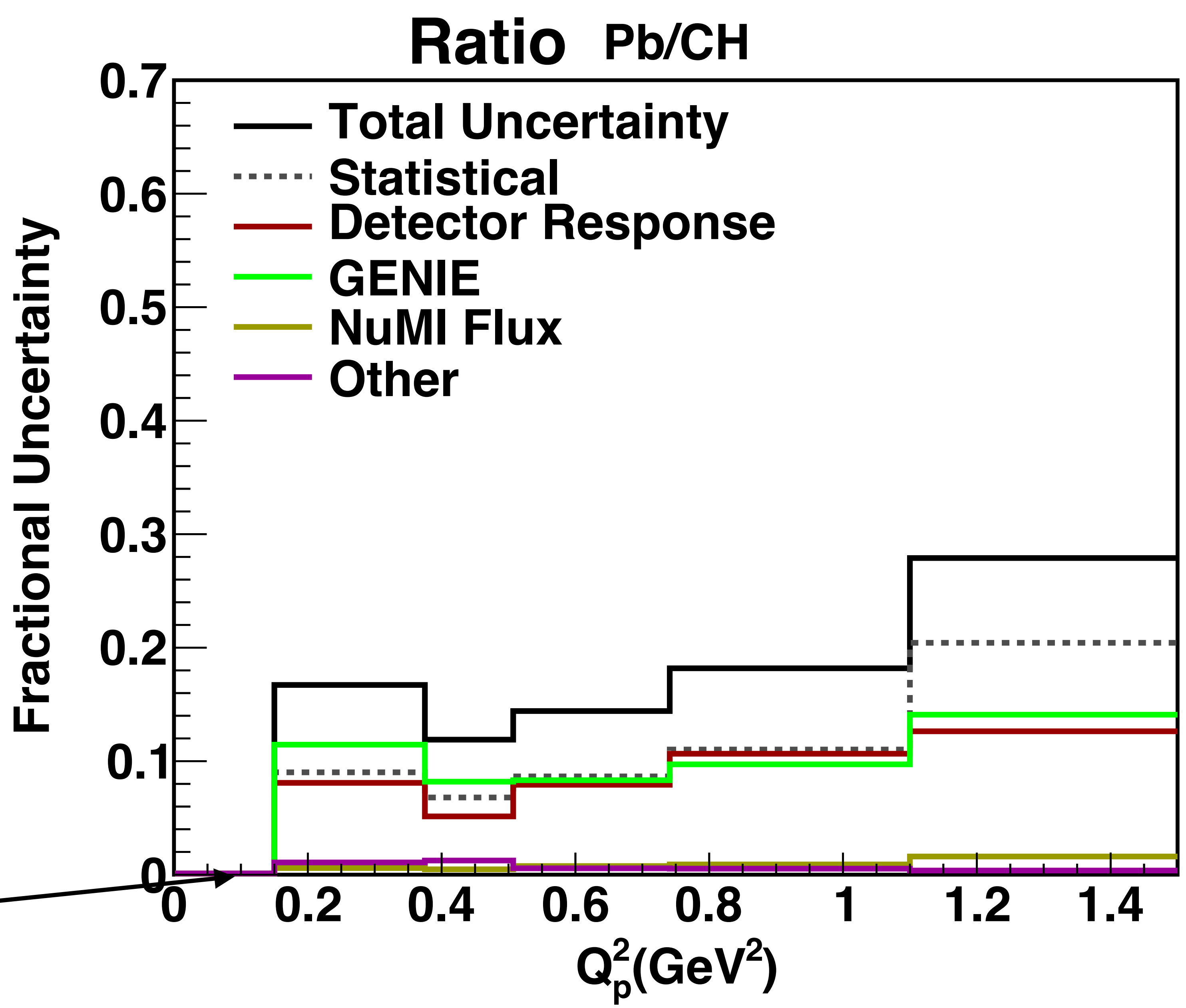


arXiv:1705.03791



Systematics

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



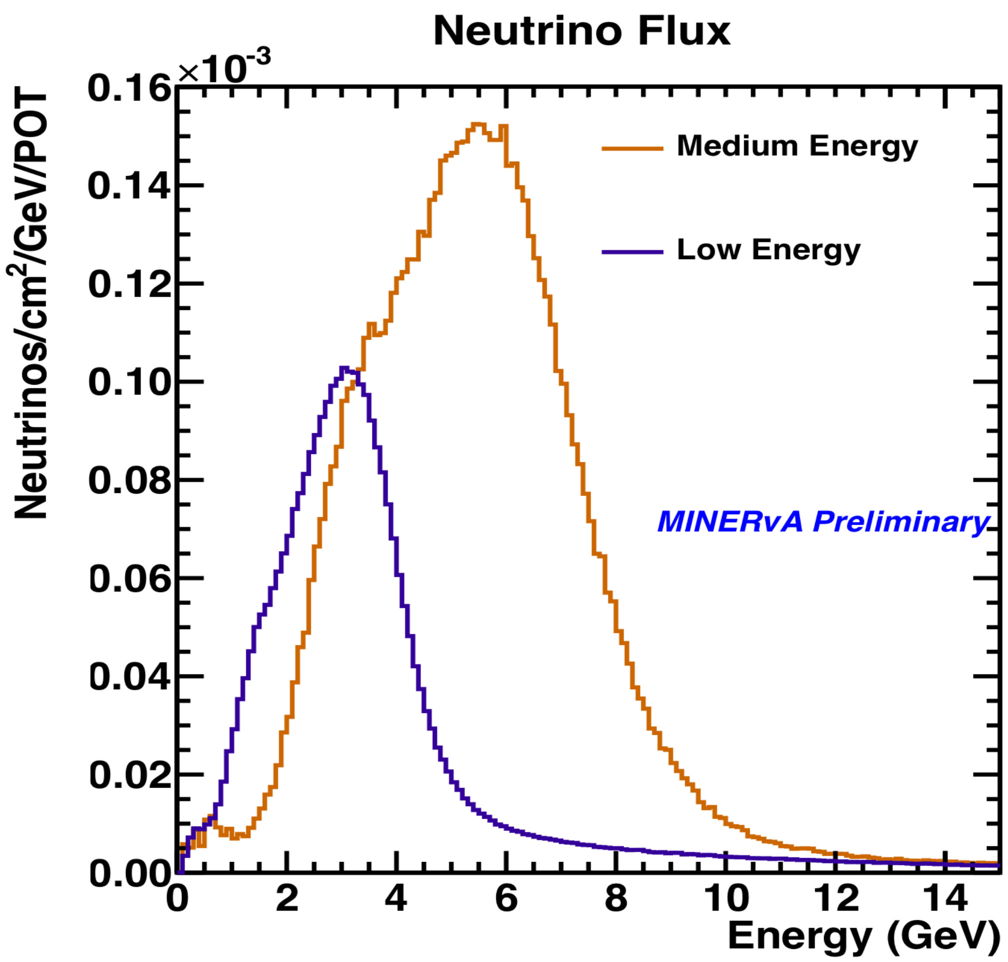
Flux uncertainty

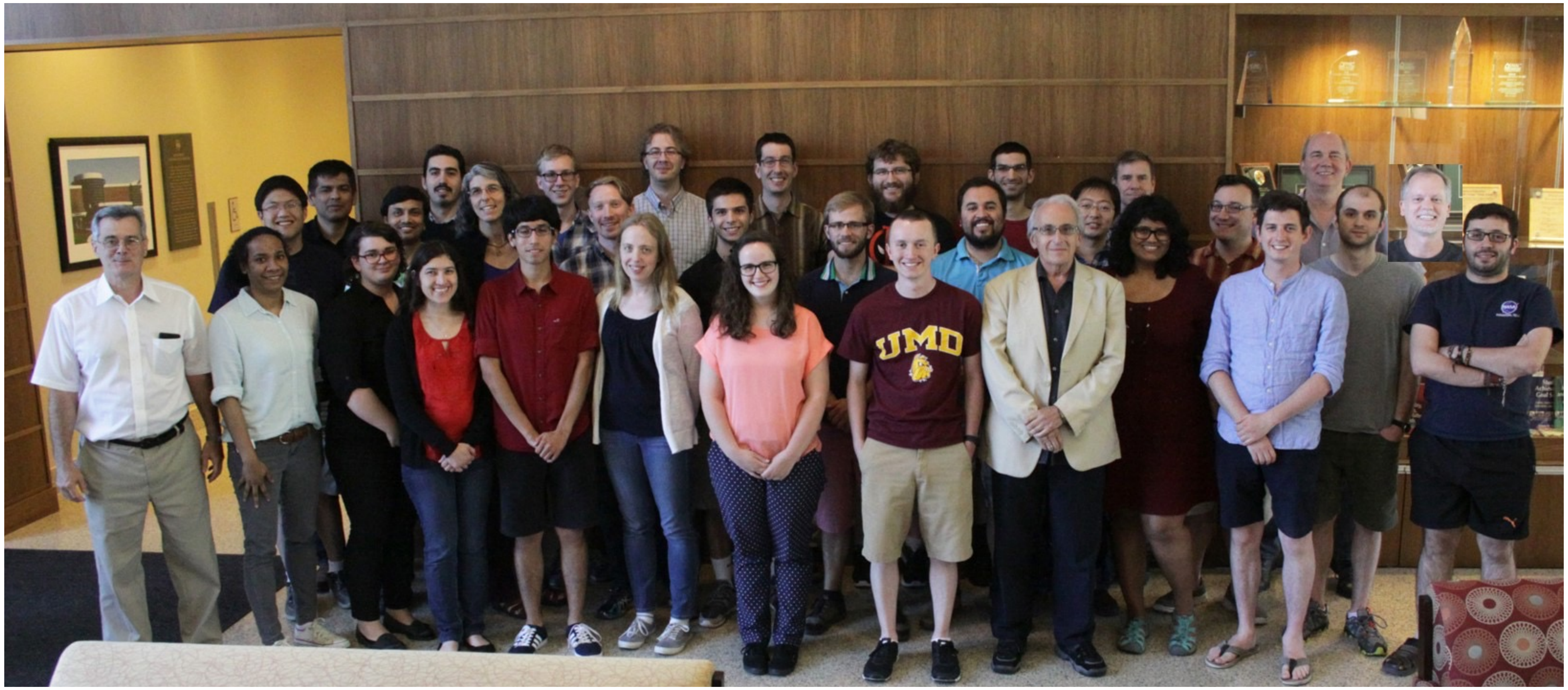
Conclusions

- 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
- 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
- Oscillation experiments depend on modeling nuclear effects correctly for precision oscillation measurements!

Future

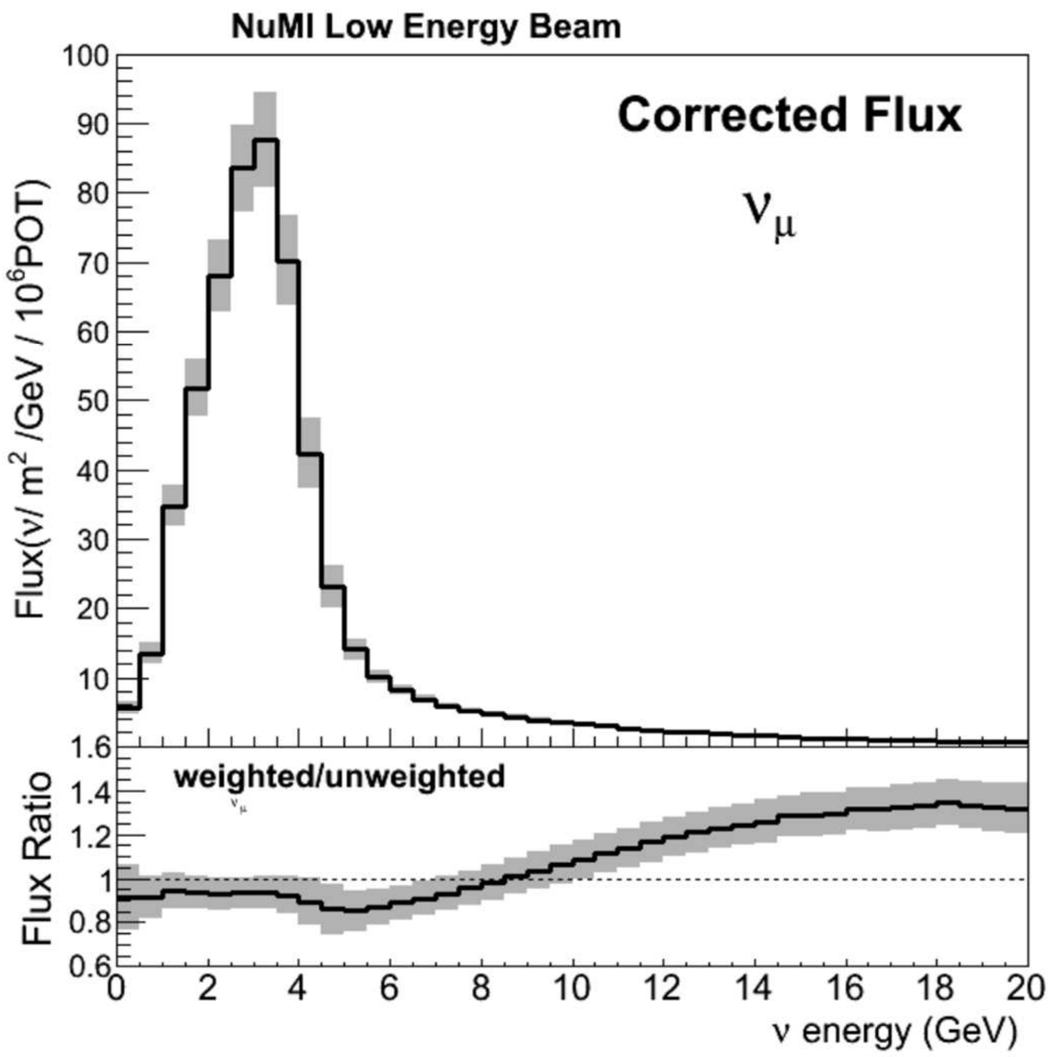
- Nuclear effects using different variables with muon+proton sample (Transverse kinematic imbalance), arXiv:1608.04655
- Measurements of quasi-elastic on scintillator, iron, lead, and carbon using the NuMI medium energy beam (A factor of 5 more statistics with access to higher Q^2 range)

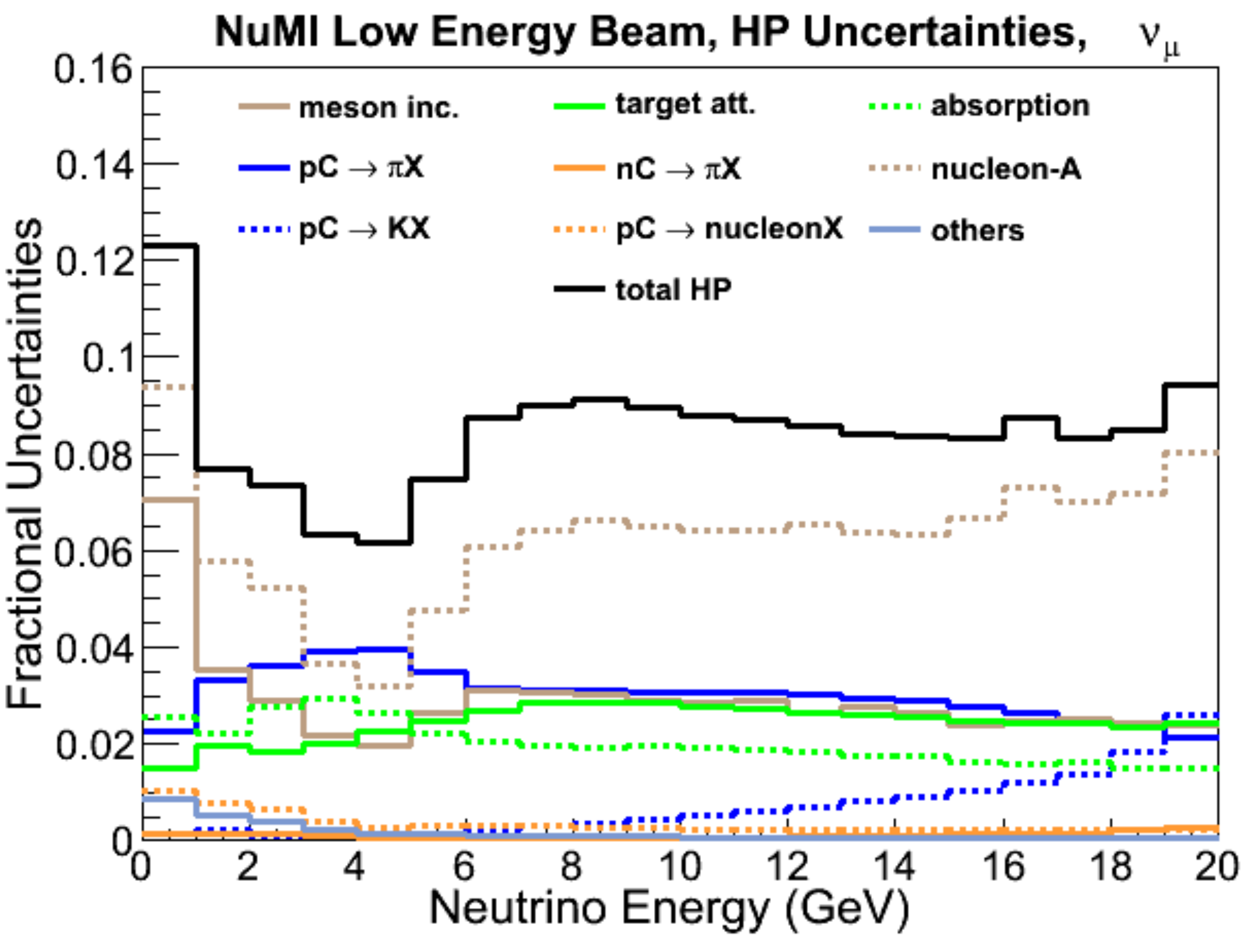




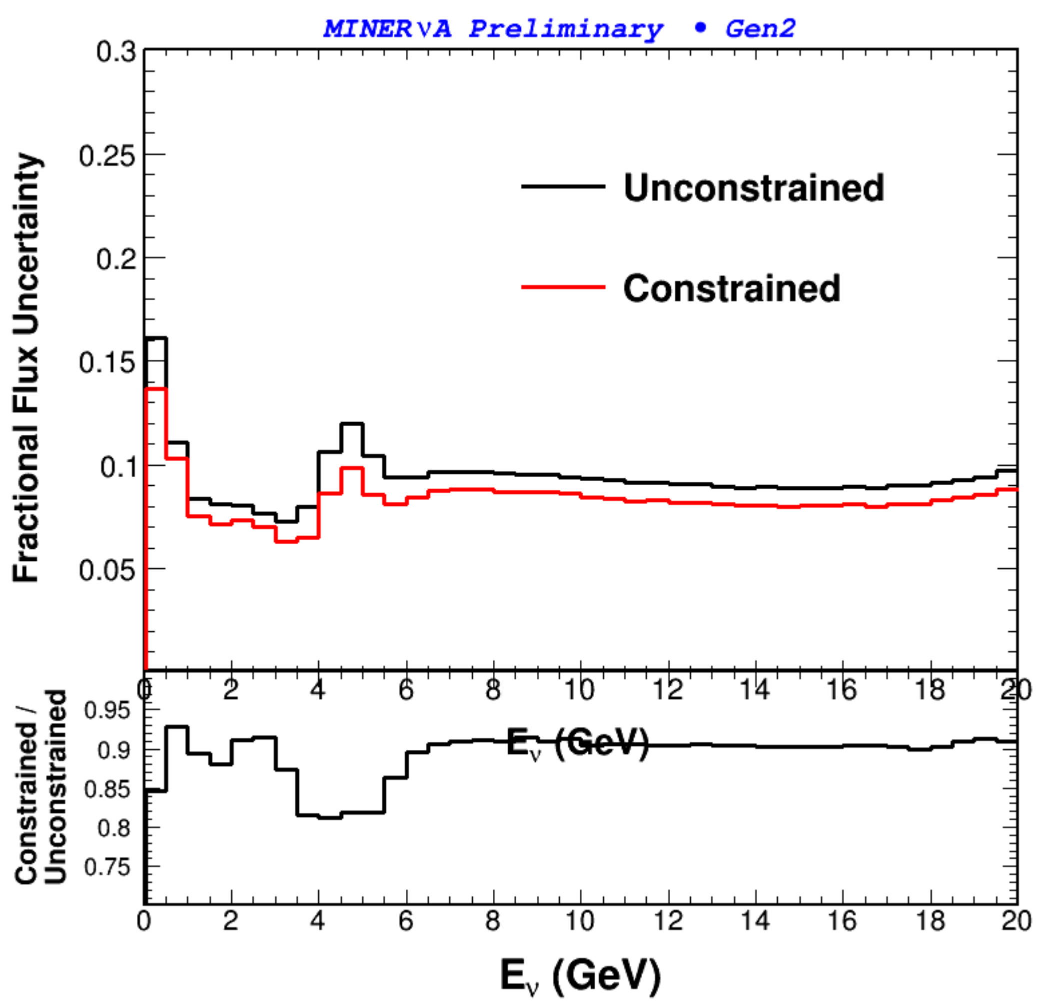
Thanks

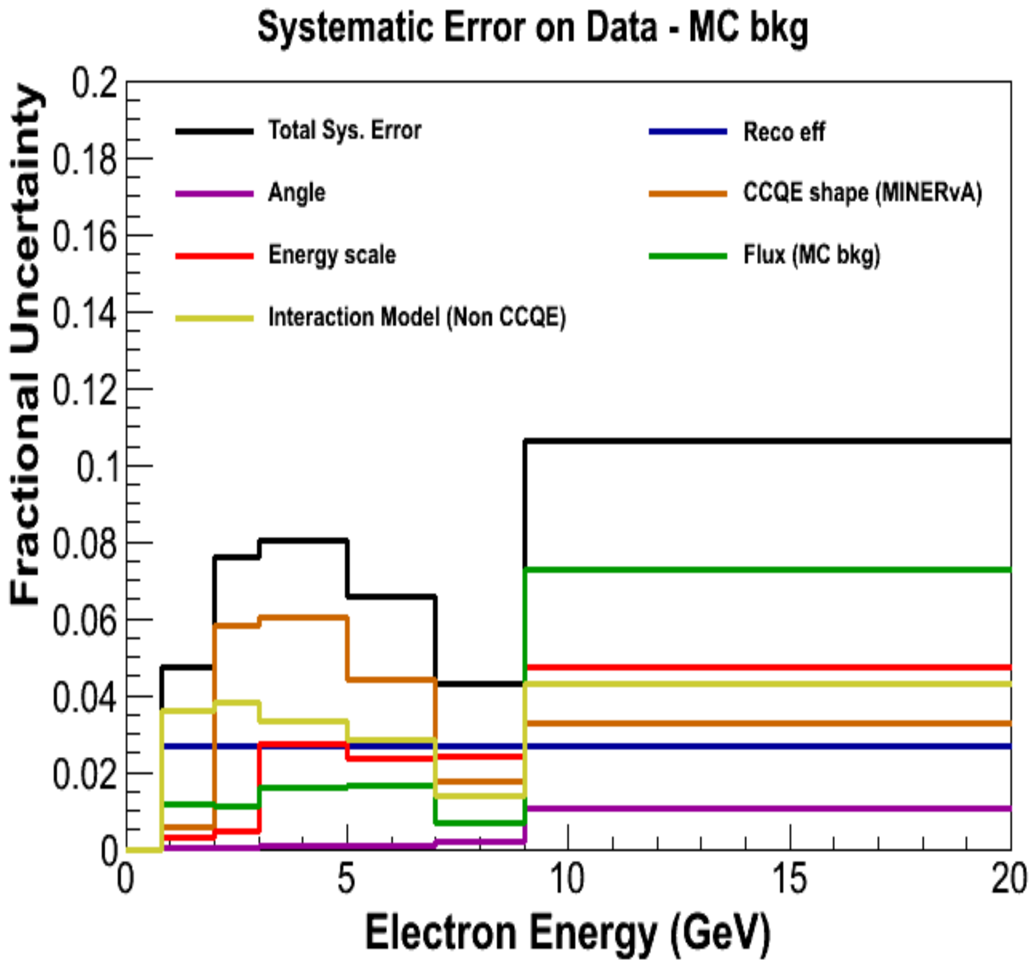
The NuMI Flux





Neutrino Electron Scattering





Phys. Rev. D 93, 112007 (2016)