Nuclear Dependence of Quasi-Elastic Scattering at MINERvA

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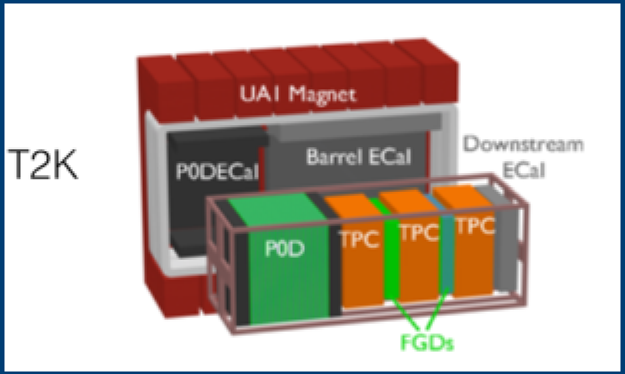
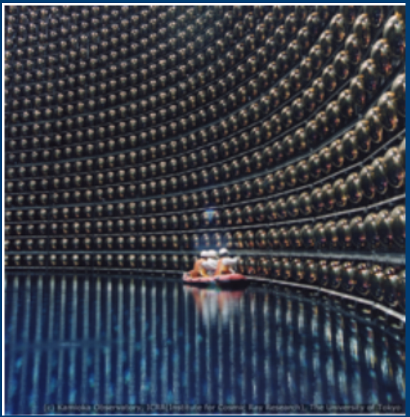
Why?

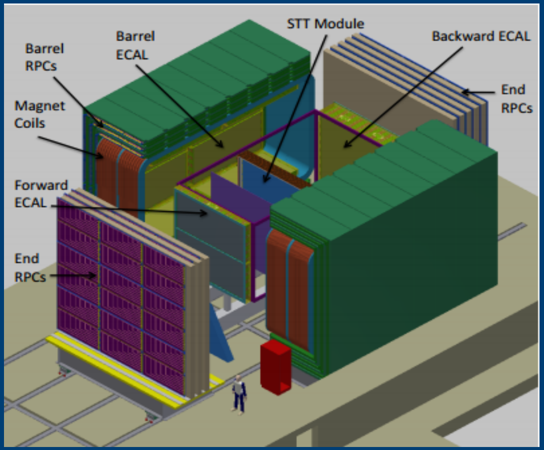
- Neutrino oscillation experiments need to accurately reconstruct E_ν
- Nuclear effects can shift reconstructed E_ν from true E_ν, can alter the content and kinematics of the particles in the final state
- In some experiments, near and far detector are constructed from different materials. This requires an understanding of how nuclear effects change in heavier nuclei
- An important interaction for many experiments is charged current quasi-elastic scattering (CCQE). Studying nuclear effects this channel will help improve the precision of their measurements



T2K Near Detector (Carbon)



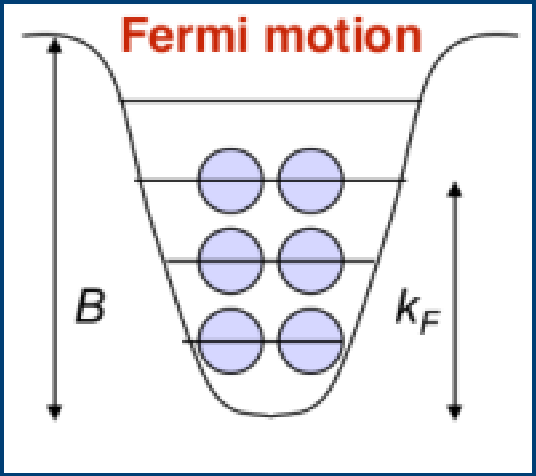
T2K Far Detector (Water)

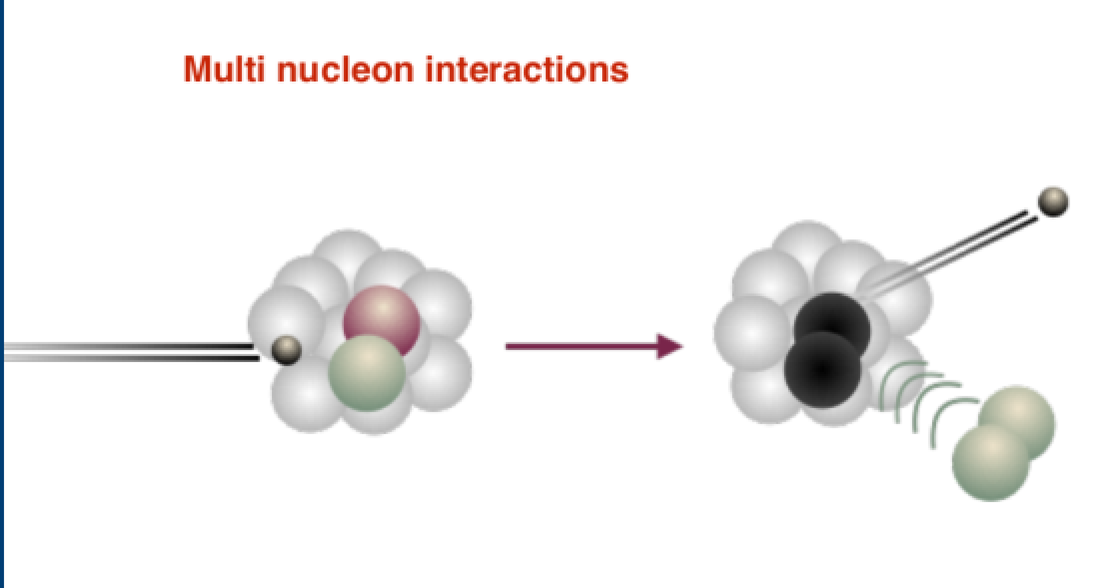


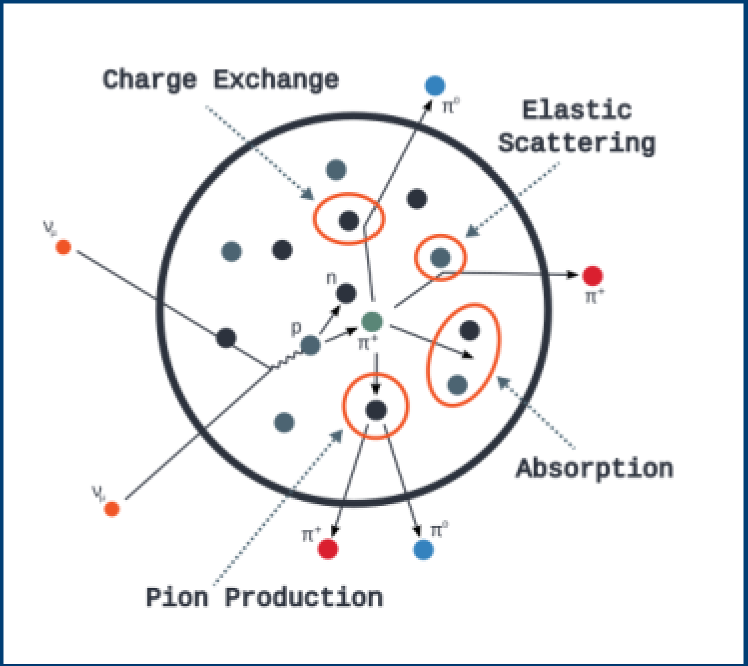
Proposed Dune Near Detector?

Nuclear Effects

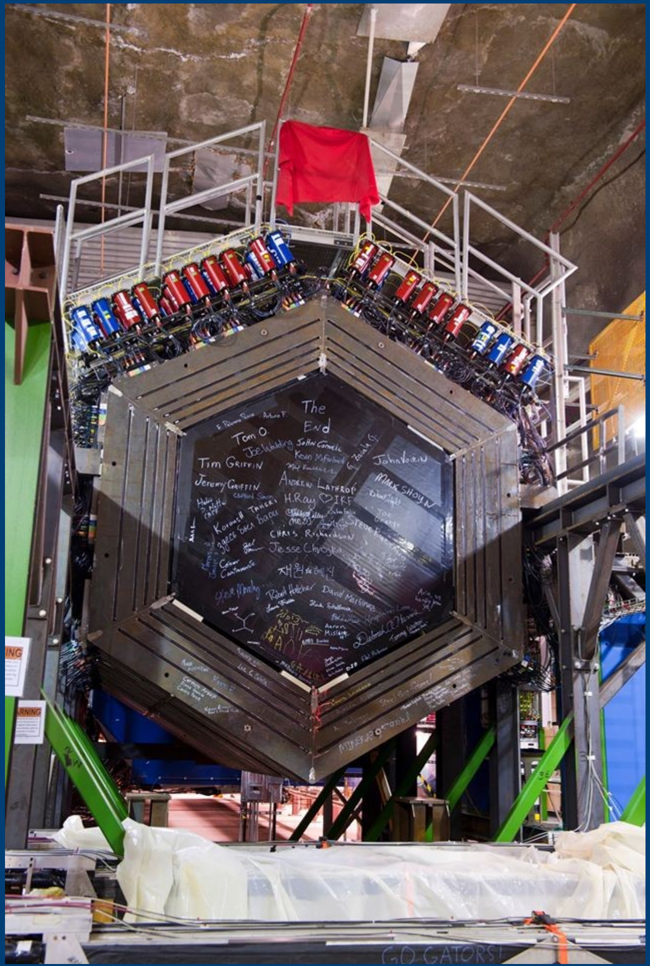
- There are a large multitude of nuclear effects that can modify the final state particles of the interaction
  - Fermi motion
  - Pauli blocking
  - Multinucleon interactions (2p2h, RPA)
  - Final state interactions

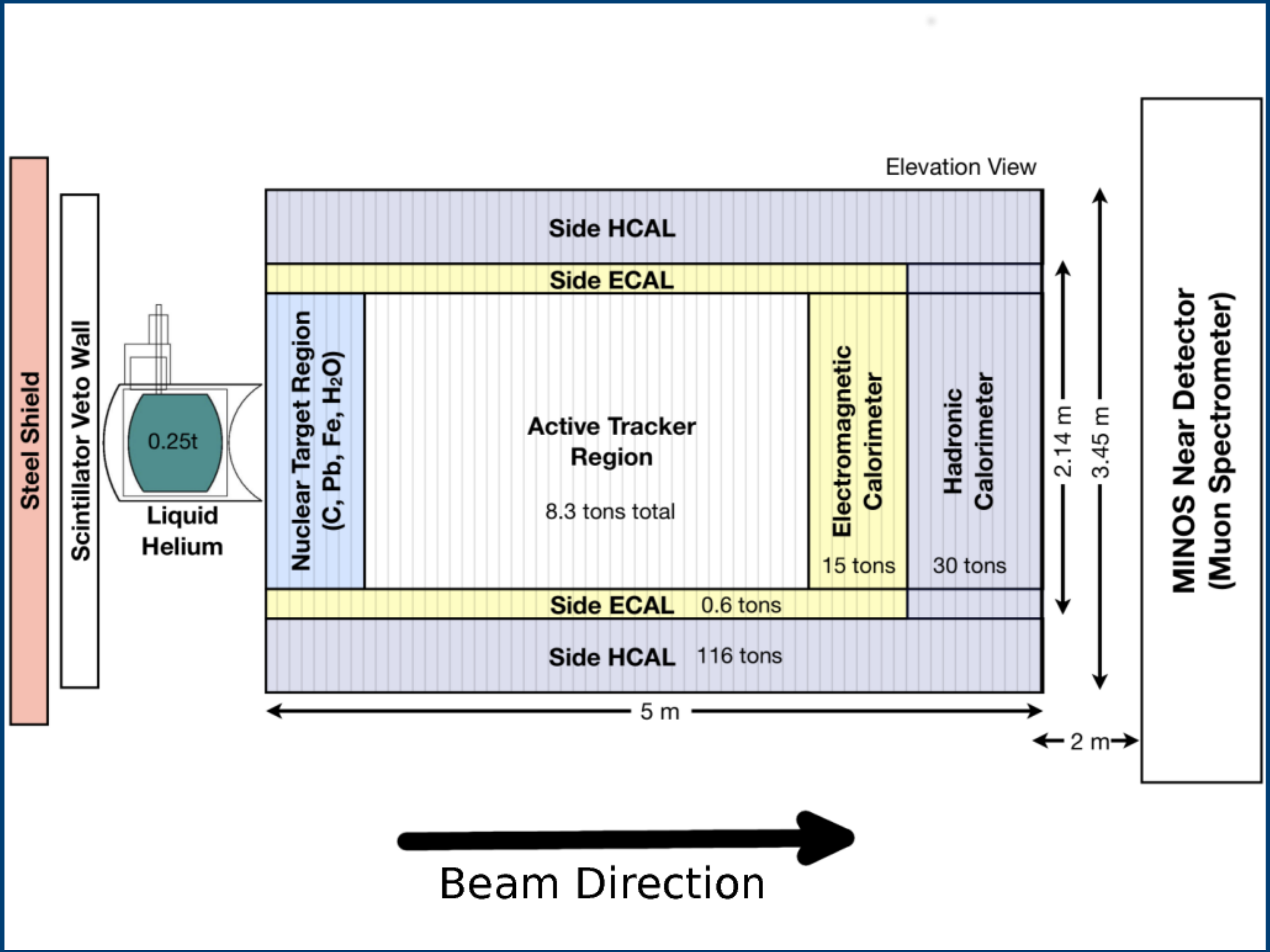




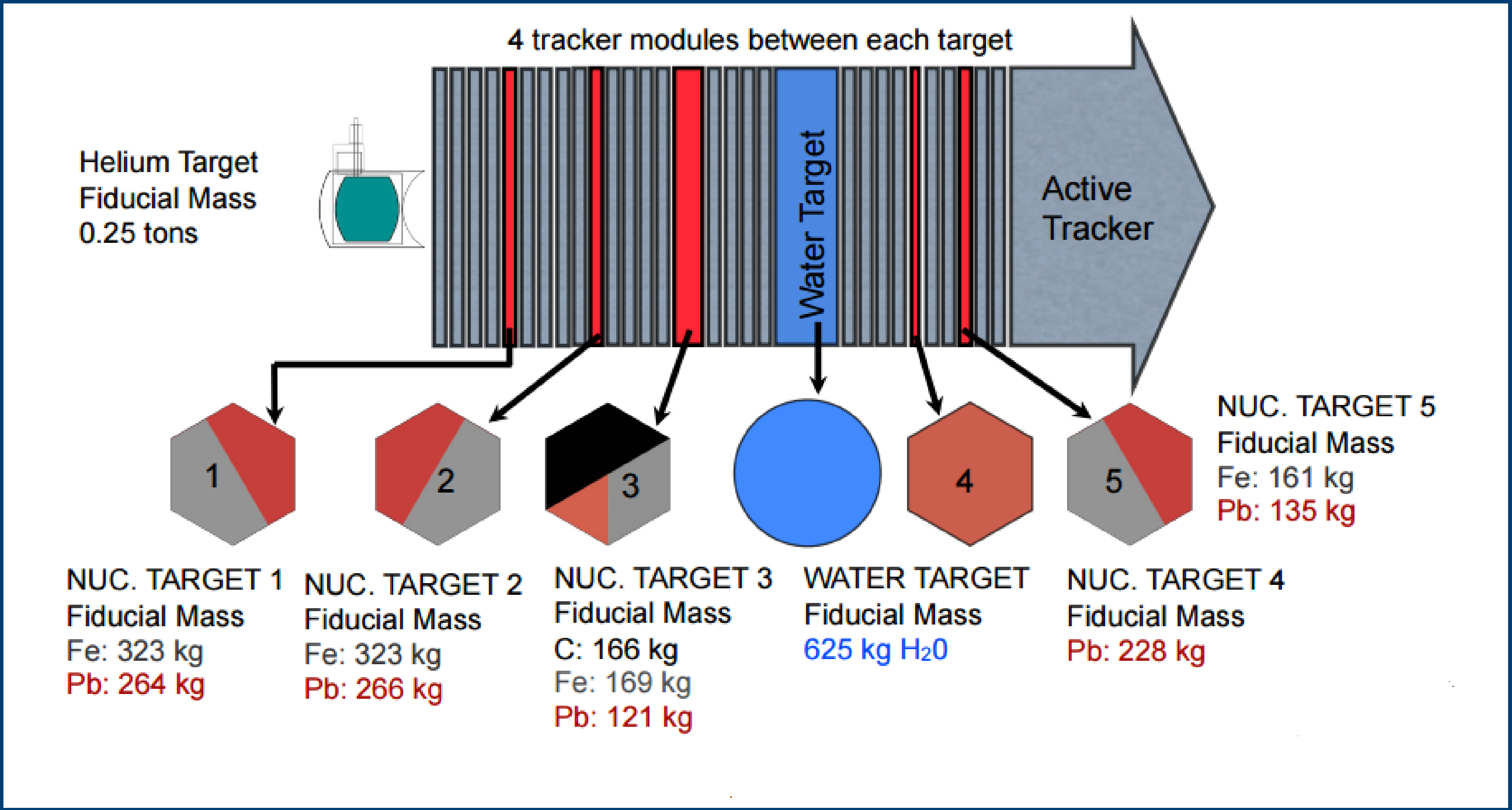


MINERvA Detector



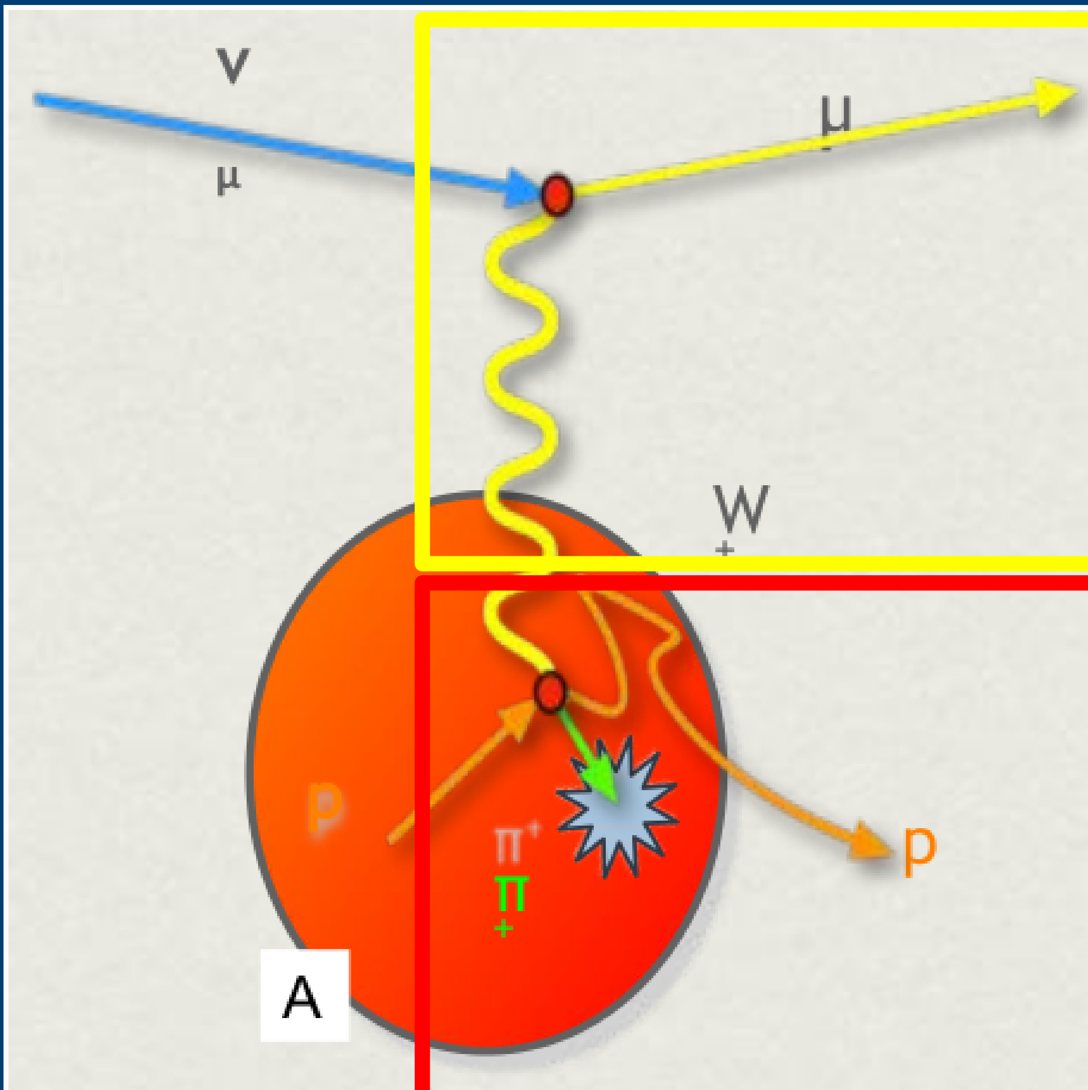


Nuclear Targets Region in MINERvA



- Measuring cross sections in the same detector allows us to cancel systematics uncertainties, such as flux and detector response

Looking at the nucleus



Lepton

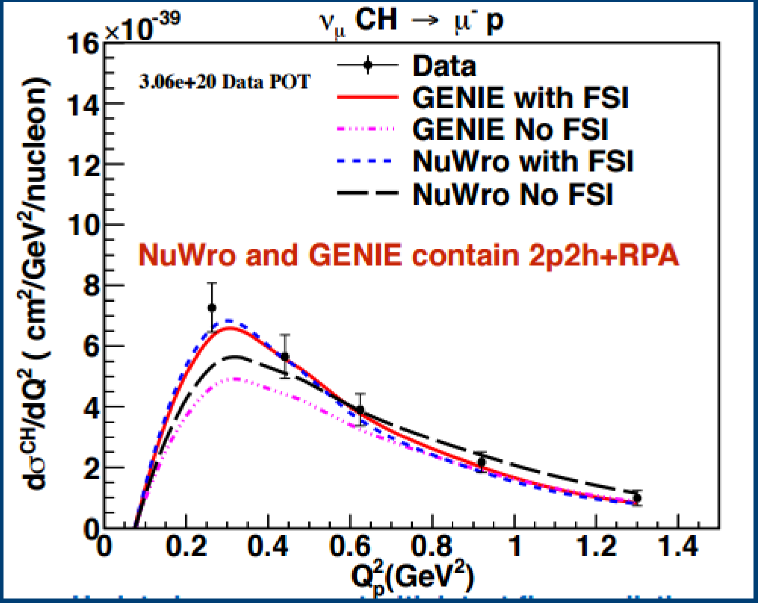
- Provides information on the initial state of the nucleons within the nucleus
- Initial State Interactions:
  - Relativistic Fermi gas Model
  - Local Fermi Gas Model
  - Spectral Functions
  - Correlated Nucleons (RPA, MEC, SRC...)

Hadron

- Undergœs final state interactions within the nucleus
  - After the interaction, previously correlated nucleon pair can also experience FSI
- By comparing to muon kinematics, allows isolation of final state effects

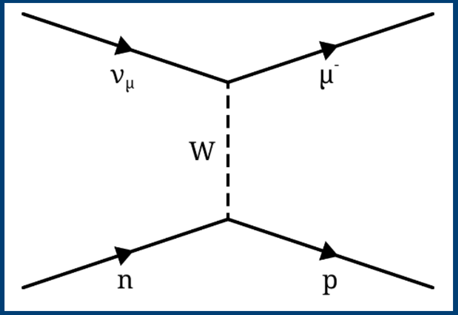
Proton Kinematics in Quasi Elastic Scattering

- Previously, MINERvA published the first differential cross section as a function of Q^2 determined from the proton, **Phys. Rev. D. 91, 071301 (2015)**
- We have updated the measurement with the latest flux prediction and the latest simulation



$$Q_p^2 = (M_n - \epsilon_B)^2 - M_p^2 + 2(M_n - \epsilon_B)(T_p + M_p - M_n + \epsilon_B)$$

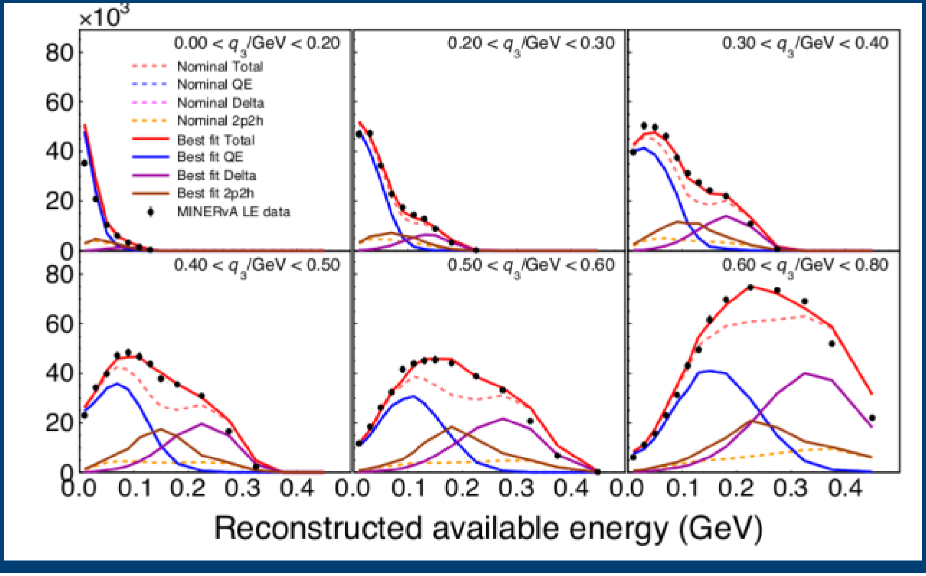
- $M_{n,p}$ = nucleon mass
- ϵ_B = effective binding energy of nucleon
- T_p = proton kinetic energy



- Q_p^2 is reconstructed using the leading proton kinematics
  - Using the QE hypothesis and assume scattering from a free nucleon at rest
  - At least one proton ≥ 450 MeV

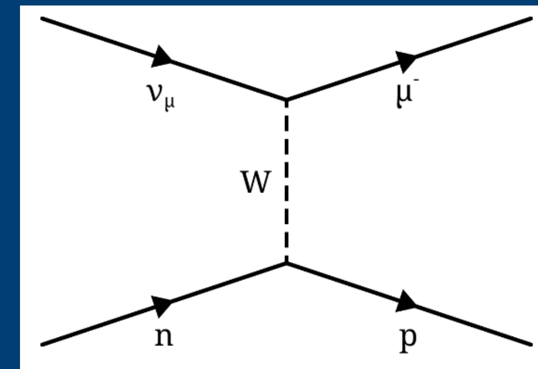
GENIE

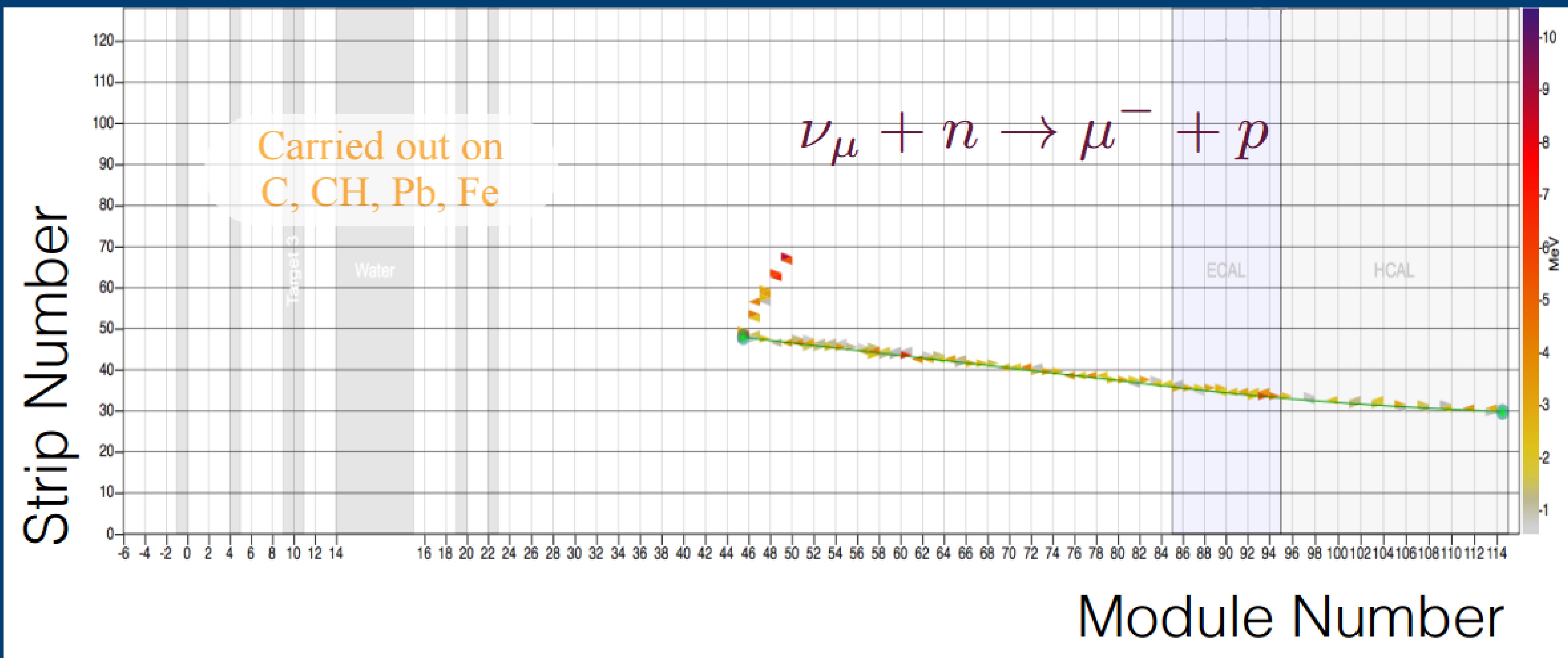
- Lately, we have implemented several improvements in modeling neutrino interactions. A large thanks to the GENIE collaboration!
- This analysis used GENIE (2.8.4) Monte Carlo generator, which generates neutrino events and is used by many experiments
- Added RPA to GENIE by reweighting QE events, **PRC 70, 055503**
- Modify non-resonance pion production to agree with deuterium data, **Rodrigues P., Wilkinson C. & McFarland K. Eur. Phys. C (2016) 76:474**
- For QE-like 2p2h processes, we included one of the theoretical predictions and the latest implementation of Valencia model **arXiv: 1601.02038, PRC 83, 045501 (2011)**
  - Reweighted 2p2h events using a 2D Gaussian defined in true variables (q_0,q_3), where the parameters are fit to get the best agreement between data and MC
  - For more info, see Jeffrey Kleykamp's upcoming talk!



CCQE Like Signal

1) One muon
2) No pions
3) At least one proton with momentum > 450 MeV/c

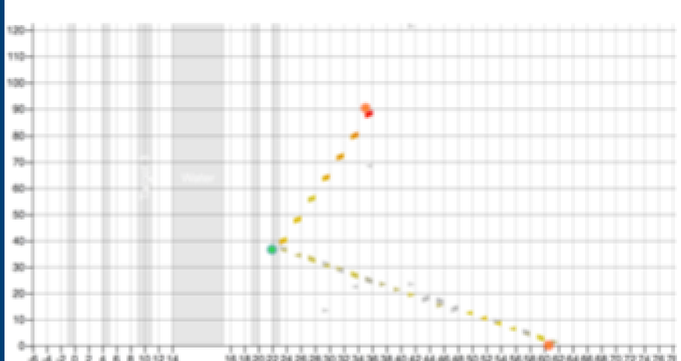




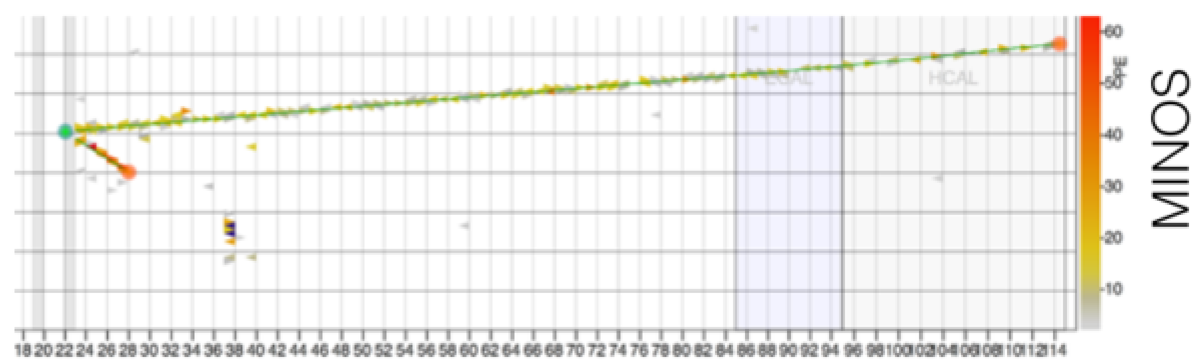
Event Selection

- At least two reconstructed tracks
  - One muon candidate
  - At least one proton candidate that stop in the detector
- Interaction vertex is reconstructed in the target material
- Proton particle identification score cut: removes events with pions
- Extra energy cut far from the vertex: remove inelastic events with untracked pion
- Michel electron cut: remove events with low energy pions

Analysis includes events with muons that exit the sides of MINERvA

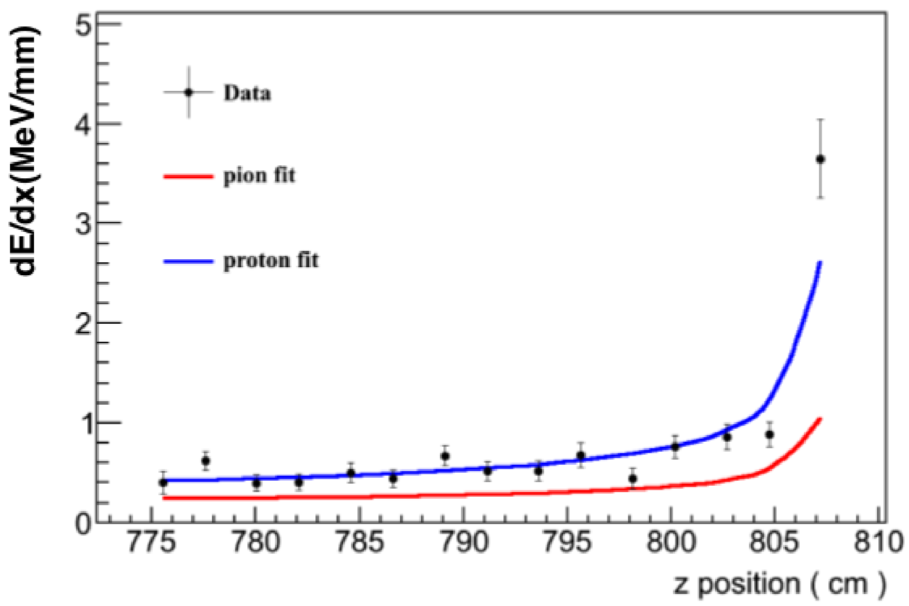


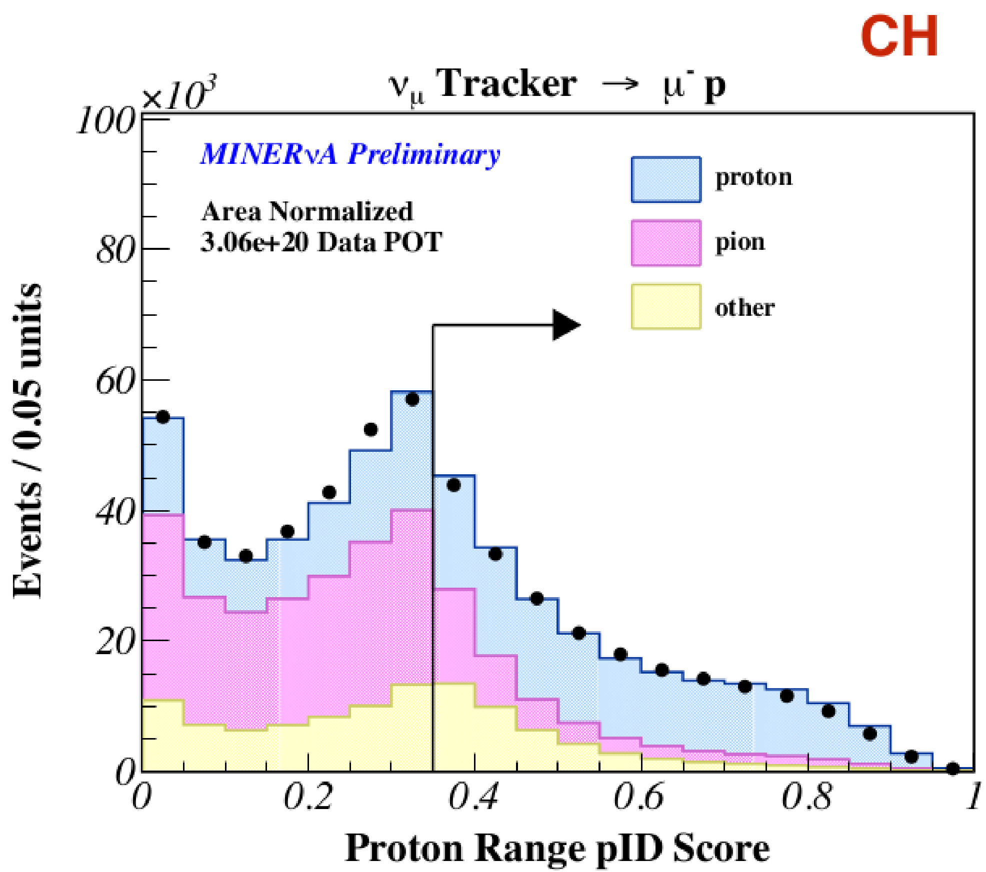
Analysis includes events with muons matched to MINOS



Selecting Proton Candidates (Proton PID Cut)

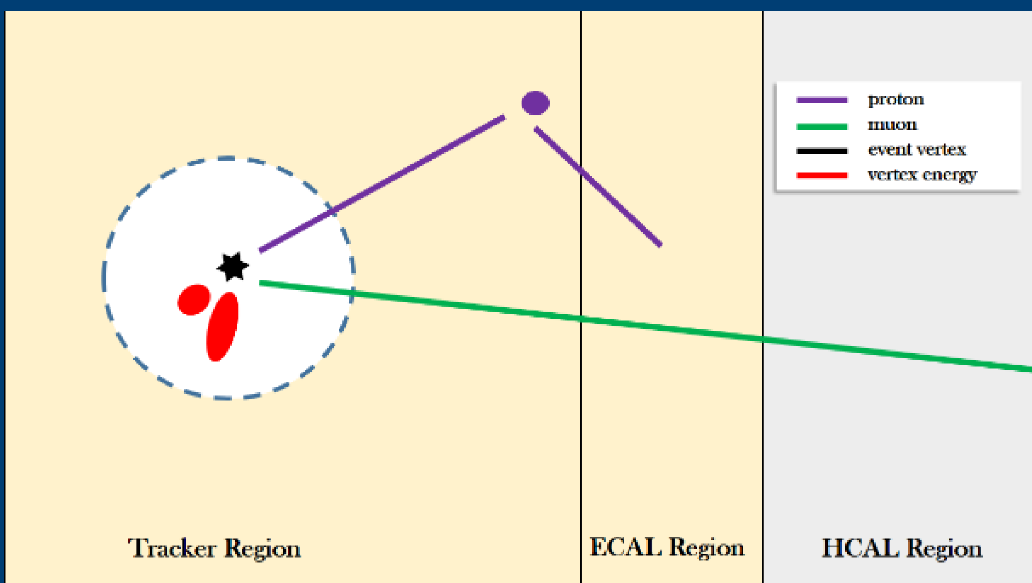
- Require events with at least one proton candidate
  - Fit each hadron track energy loss (dE/dX) profile to both proton and pion loss profiles
  - Using χ^2/dof from the proton and pion fits, create a score and select the proton candidate



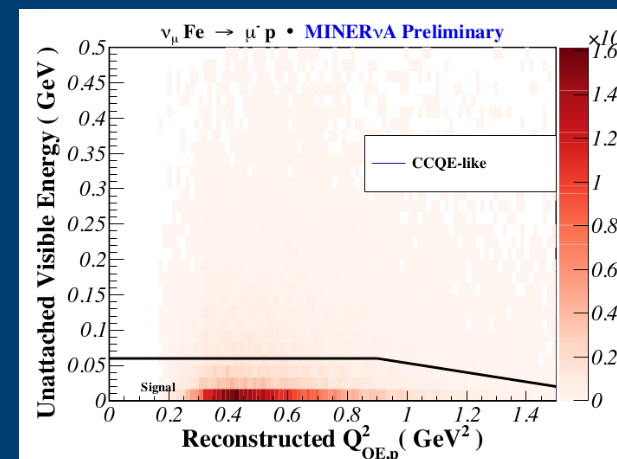


Removing Background Events

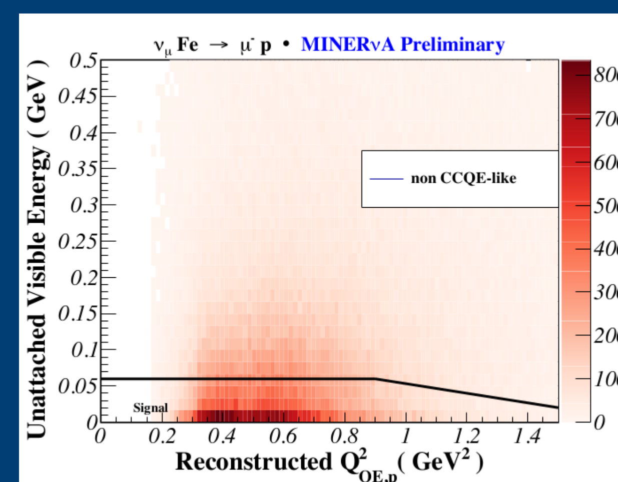
- Define a variable called unattached visible energy, which is the sum of the energy outside of the sphere (r=10cm) centered on the interaction vertex
- Looking for untracked particles produced from high recoil events
- Signal and background have different distributions in Q_p^2 vs unattached visible energy, can be use to reject background



Signal

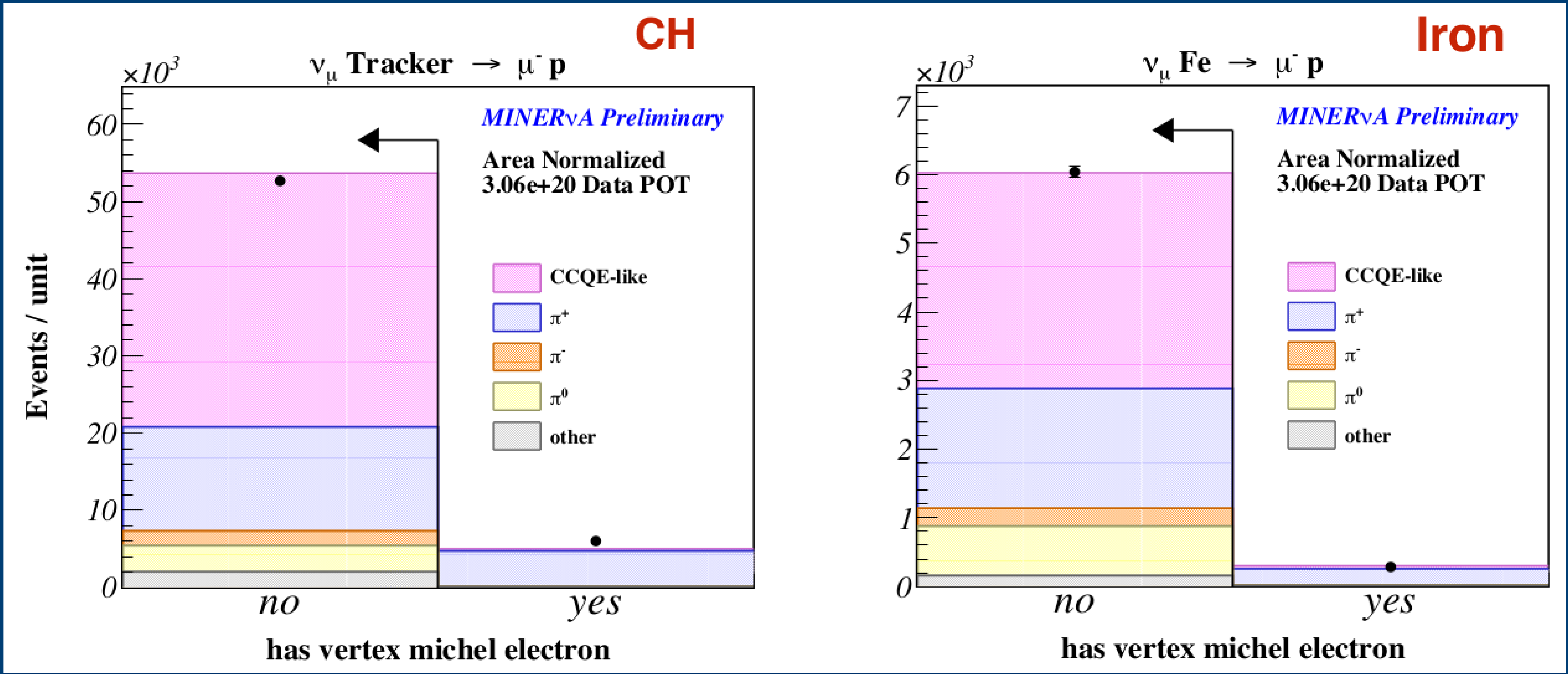


Background

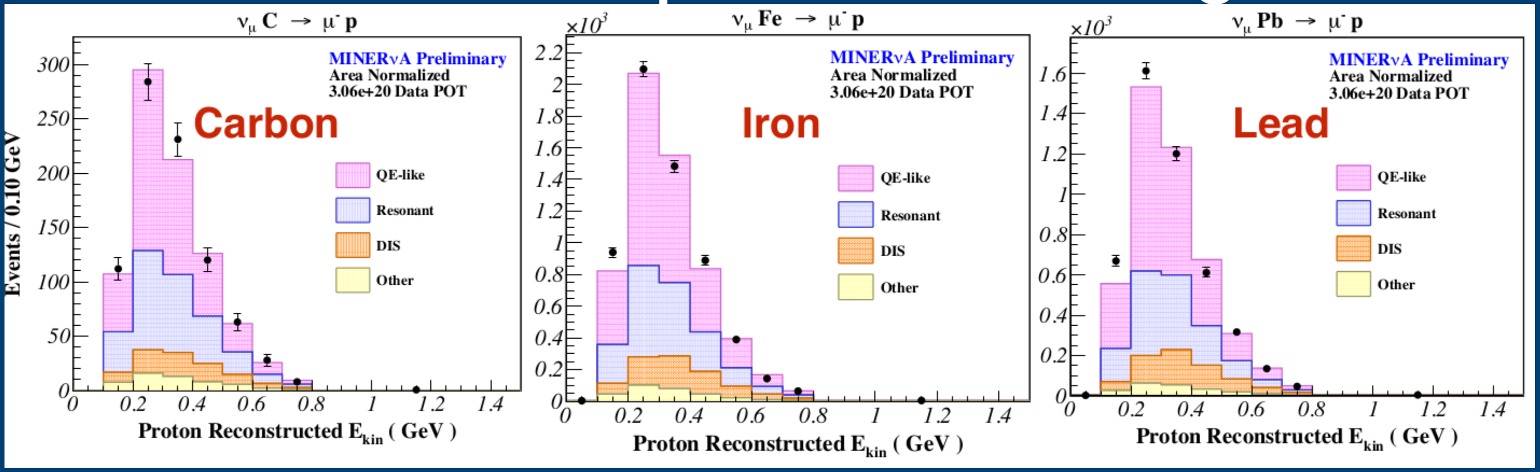


Michel Electron Cut

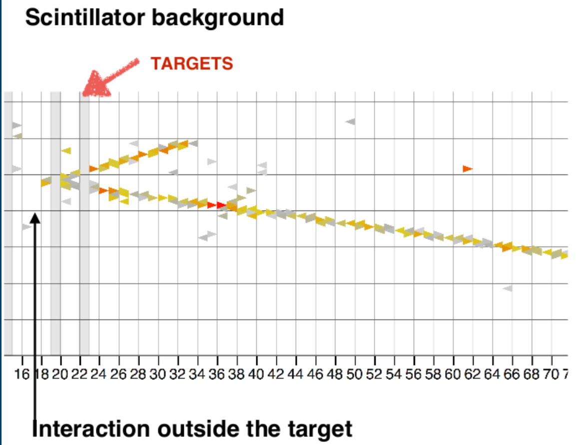
- Remove events with michel electrons
  - Helps remove low energy pions

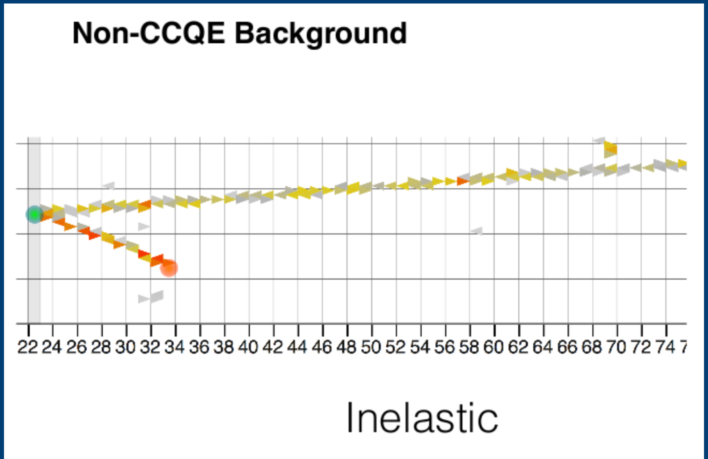


Selected Sample and Background



- Looking at our selected sample, ~30% pion production through baryon resonances
- ~10% are Deep Inelastic Scattering (DIS)
- Two main backgrounds
  - Scinitllator: mis-reconstructed events which occurred outside the nuclear targets
  - Non CCQE-like: pions have been misidentified as protons





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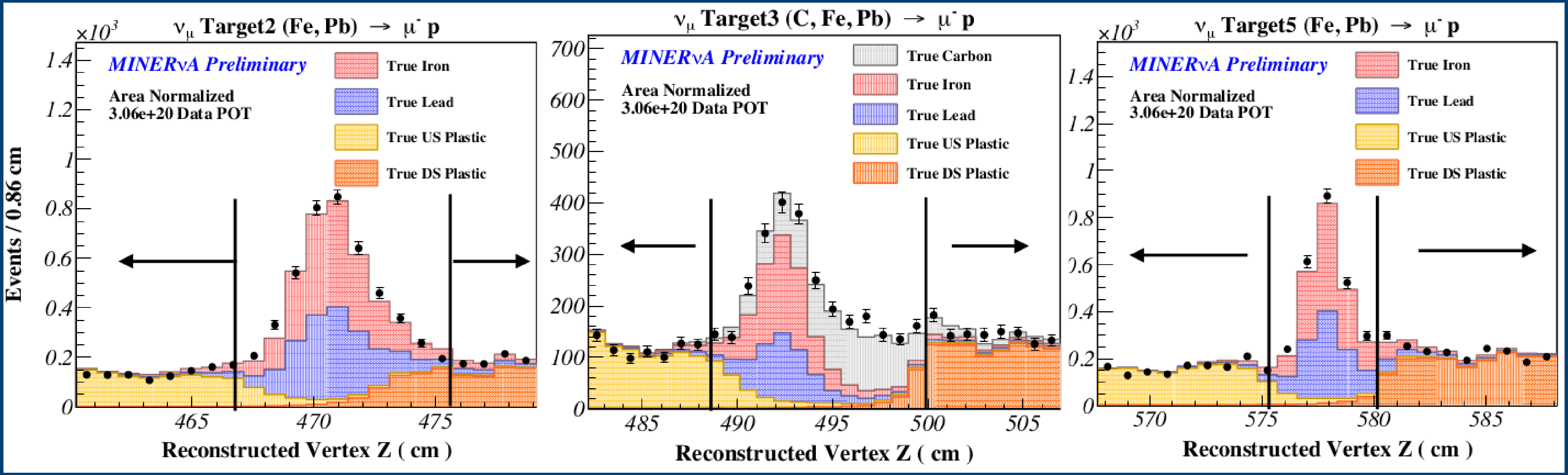
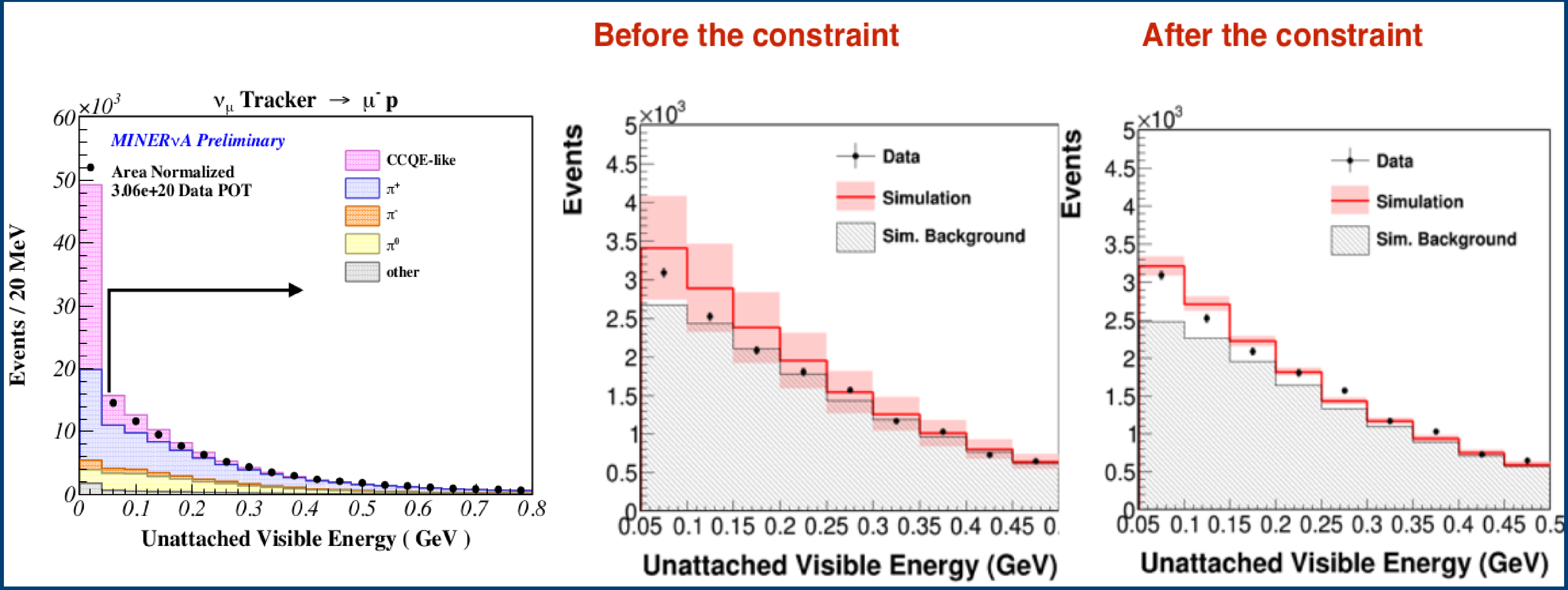
Constraining the Scintillator Background

- The distributions outside the target z cut are dominated by scintillator events
- Regions outside the fiducial volume are used to constrain the scintillator background
- Fit the distributions outside the z cut for each target separately and extract a scale factor for the scintillator background

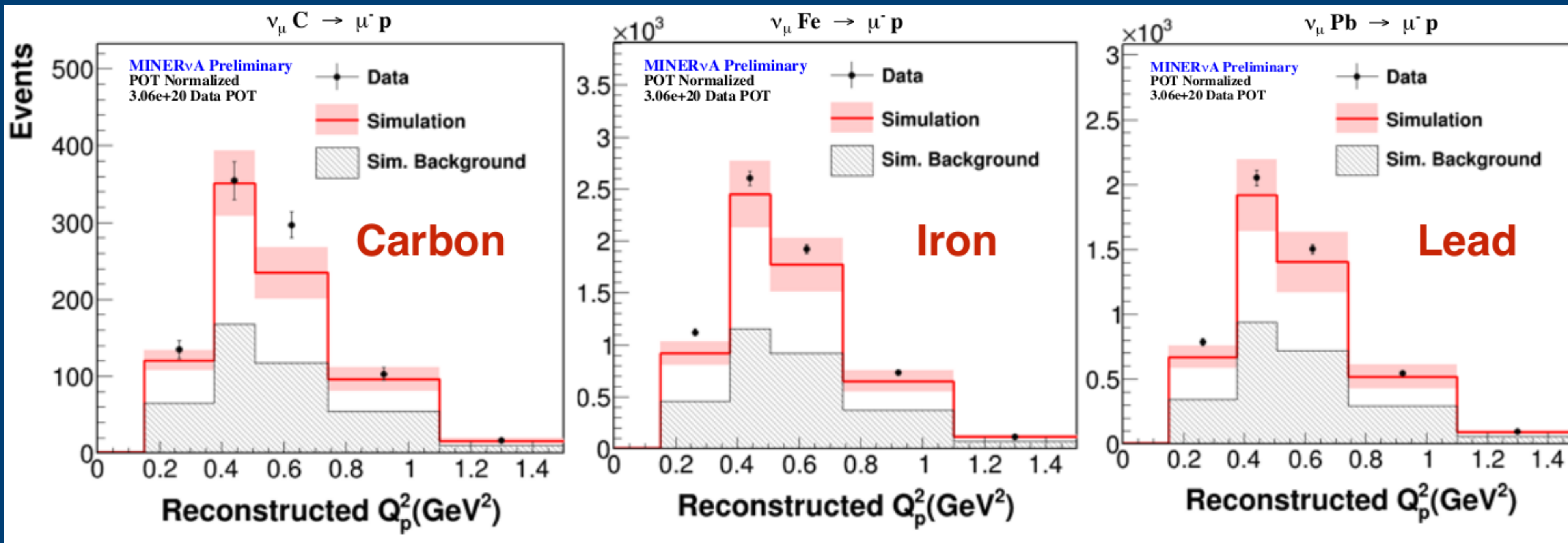


Constraining Non CCQE-Like Background

- Taking the distribution of unattached visible energy for event passing the proton pID in the tracker, separate the sample into two different bins of Q^2
- Keeping the signal constant, allow the background to float in a fit in the background dominated region



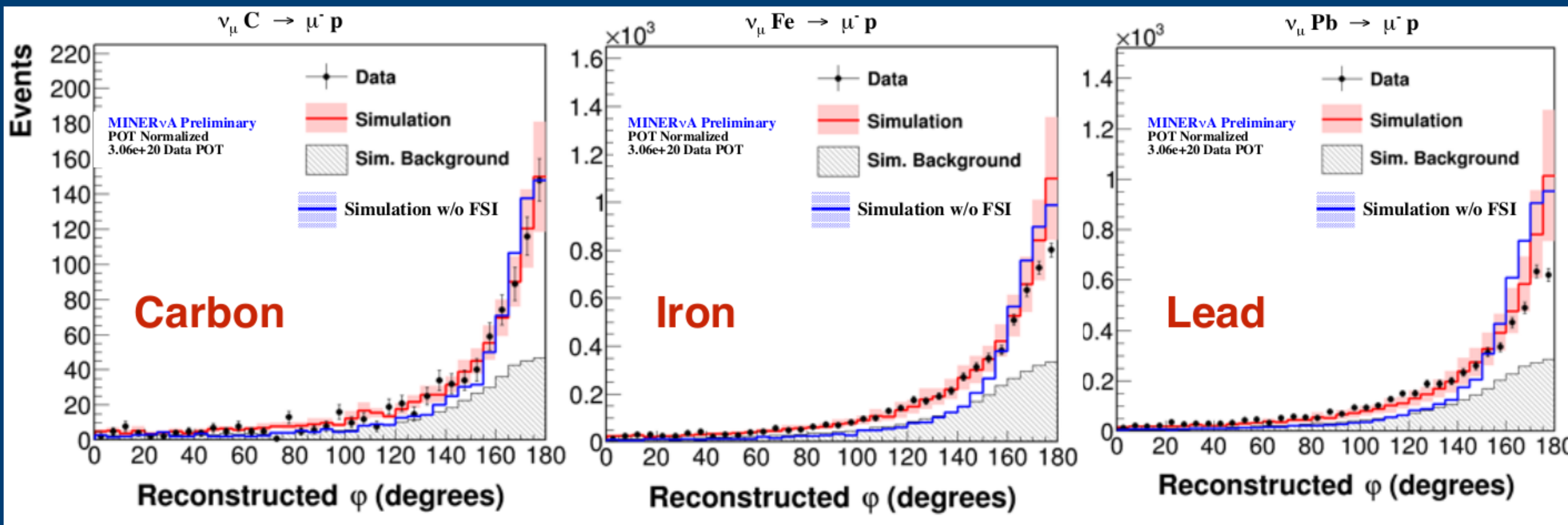
Reconstructed Proton Q^2



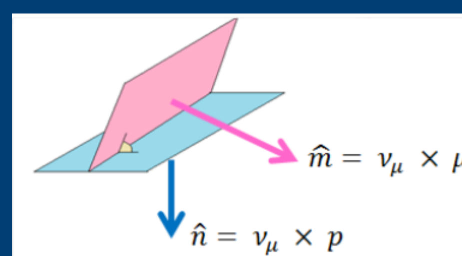
- After all the previous cuts, with tuned background
- Distributions contain the background from the scinitillator

Coplanarity Angle

- After all the cuts, with tuned background, first look at FSI effects
- One can study the coplanarity angle to isolate nuclear effects
- With no FSI and target nucleon at rest, coplanarity angle = 180. Any deviation is due to the nuclear medium



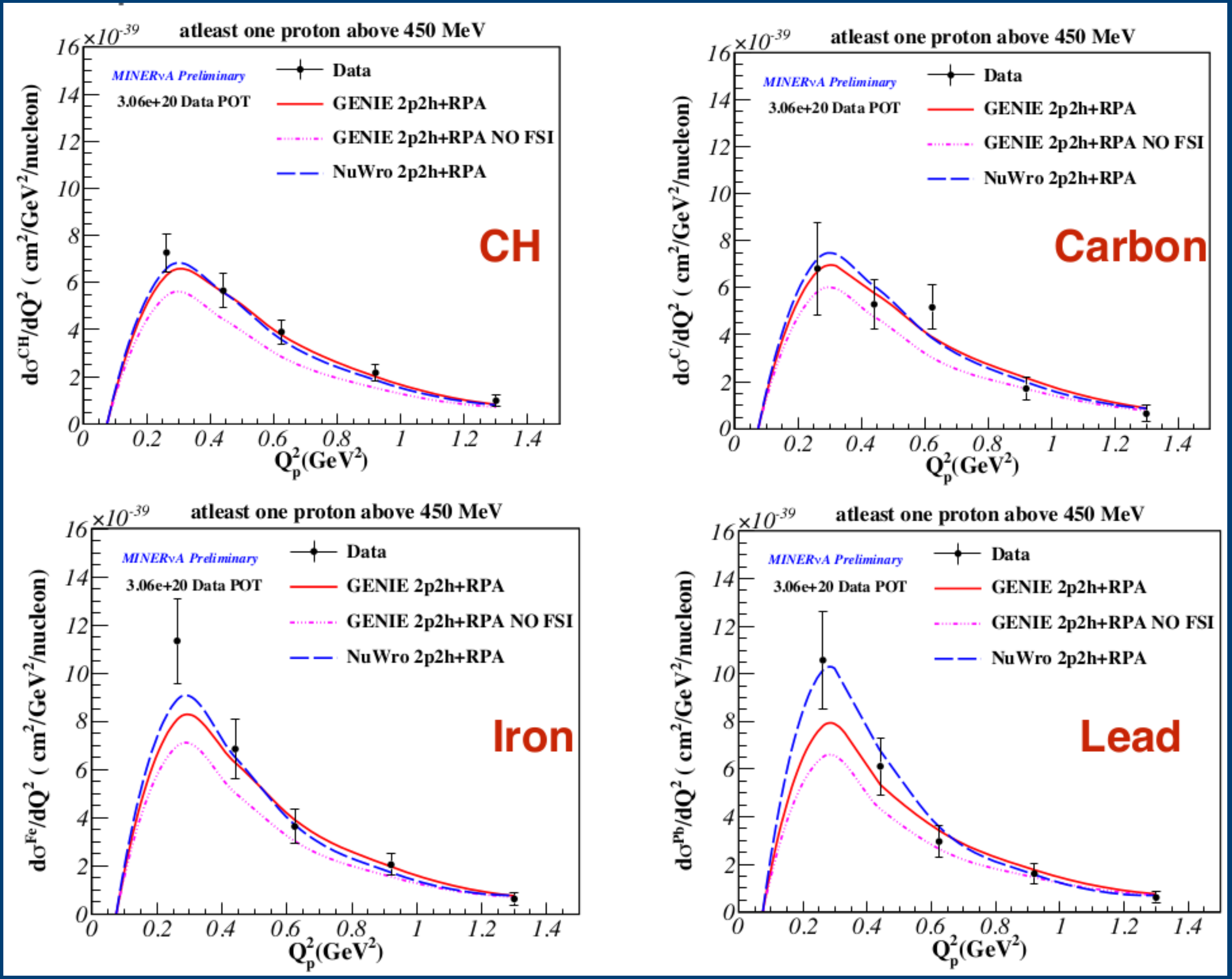
- In the MC, FSI affects the width of the peak
  - Data agrees with simulation with FSI
- Discrepancy between Data/MC at peak increases with A



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

Differential cross section measurements

- Both NuWro and GENIE include 2p2h effects and RPA
- Data favors the FSI with A-dependence predicted by the NuWro generator

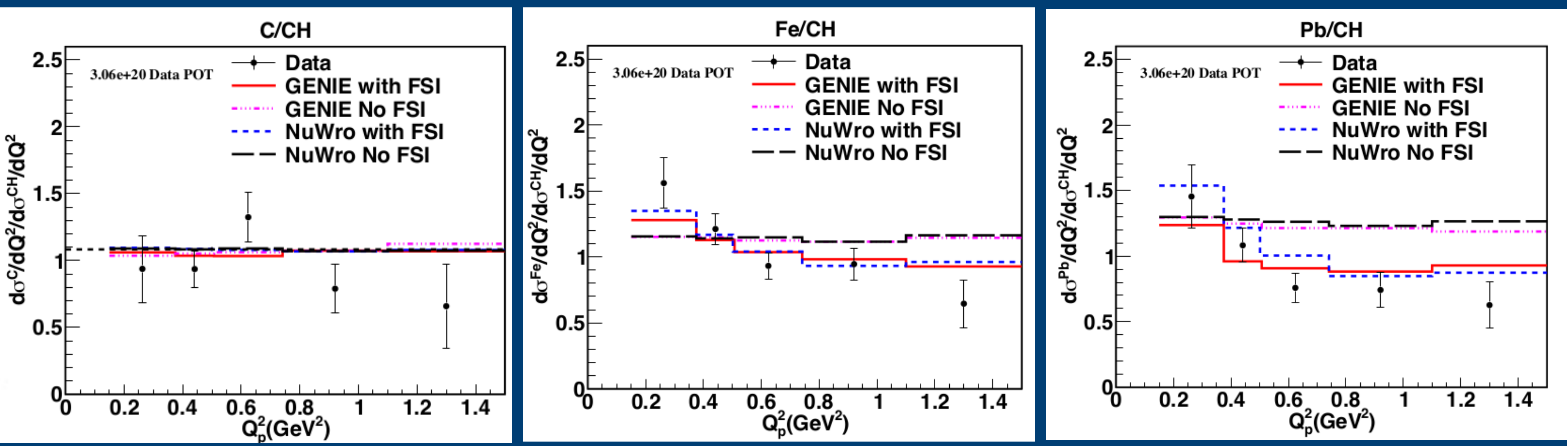


χ^2/d.o.f

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

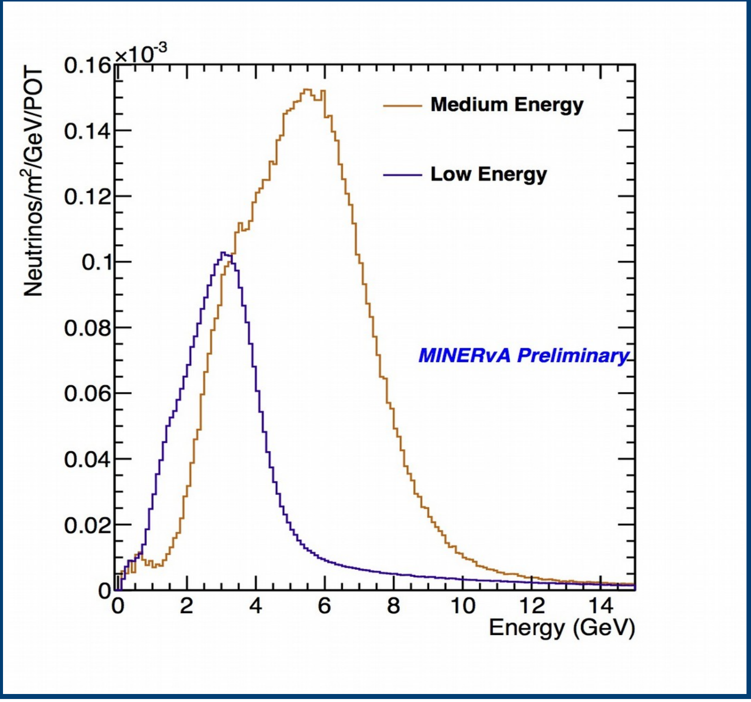
Ratio of Differential Cross Sections

- These are the first CCQE measurements in the nuclear targets to study Q_p^2 dependence of nuclear effects
- Ratios help reduce systematics uncertainties (ie. flux)
- Shows the A-dependence in nuclear effects



Conclusions and Future

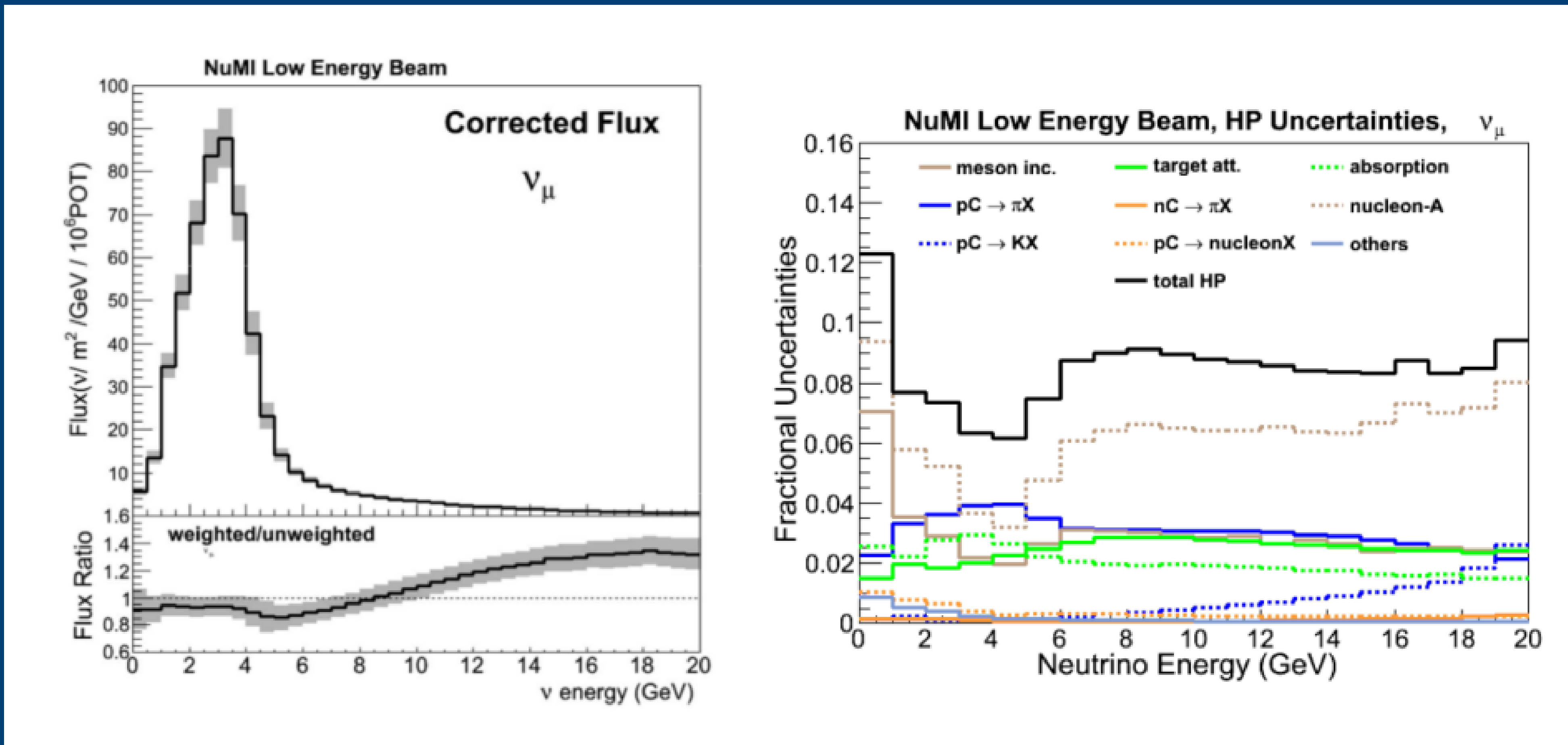
- Oscillations experiments depend of modeling nuclear effects correctly for precision oscillation measurements!
- We have shown new measurements of quasi-elastic like events on multiple nuclei (carbon, iron, lead) in an identical neutrino beam
- Previous studies have looked at nuclear effects using different variables with a muon+proton sample **(arXiV: 1608.04655)**
- Comparisons between different nuclei can probe FSI and 2p2h effects
- Data also prefers the FSI with A-dependence that NuWro predicts
- Many exclusive channel measurements will be performed in the NuMI medium energy beam, yielding higher statistics and a larger Q2 range



Thanks For Listening

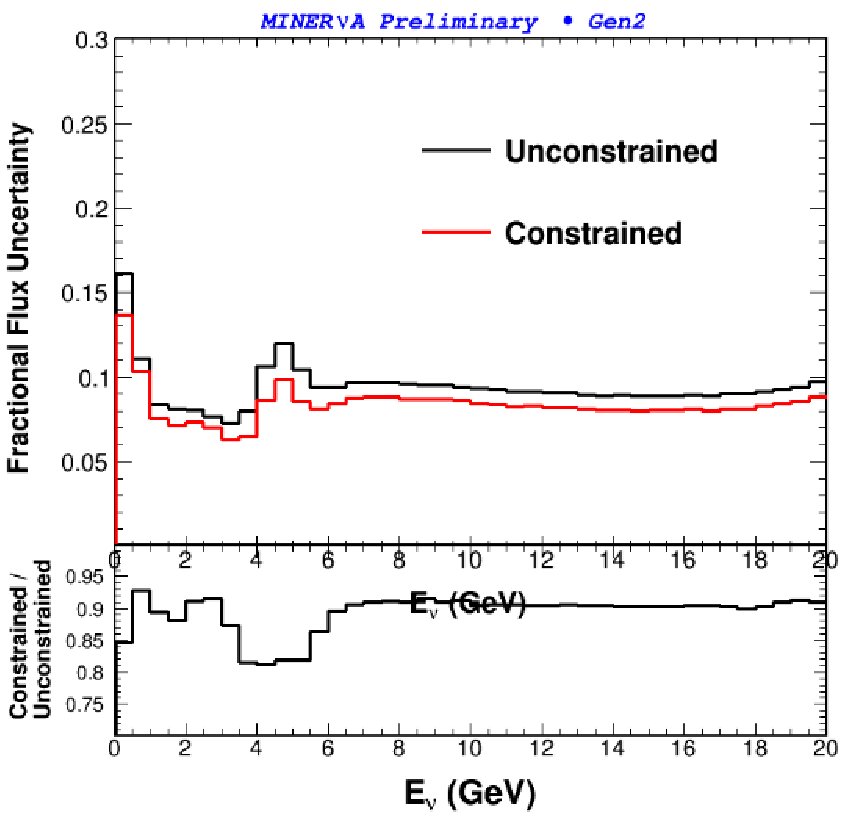
Backup Slides

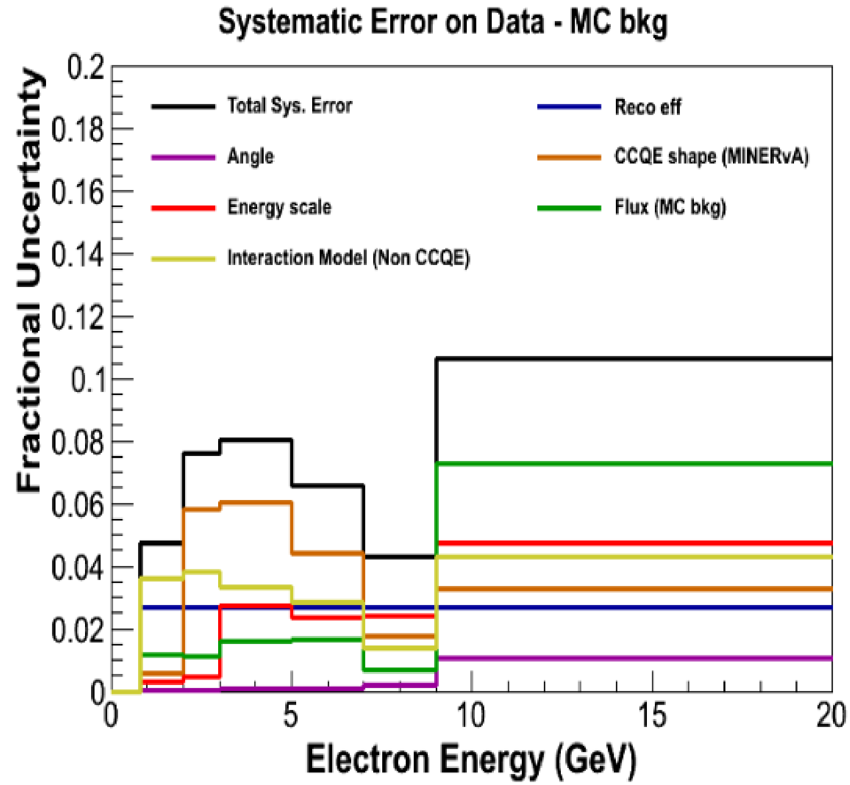
NuMI Flux



NuMI Low Energy Beam
Corrected Flux
ν_μ
Flux(ν/ m^2 /GeV / 10^{6}POT)
weighted/unweighted
Flux Ratio
ν energy (GeV)
NuMI Low Energy Beam, HP Uncertainties, ν_μ
meson inc.
target att.
absorption
pC → πX
nC → πX
nucleon-A
pC → KX
pC → nucleonX
others
total HP
Fractional Uncertainties
Neutrino Energy (GeV)

Neutrino Electron Scattering Constraint

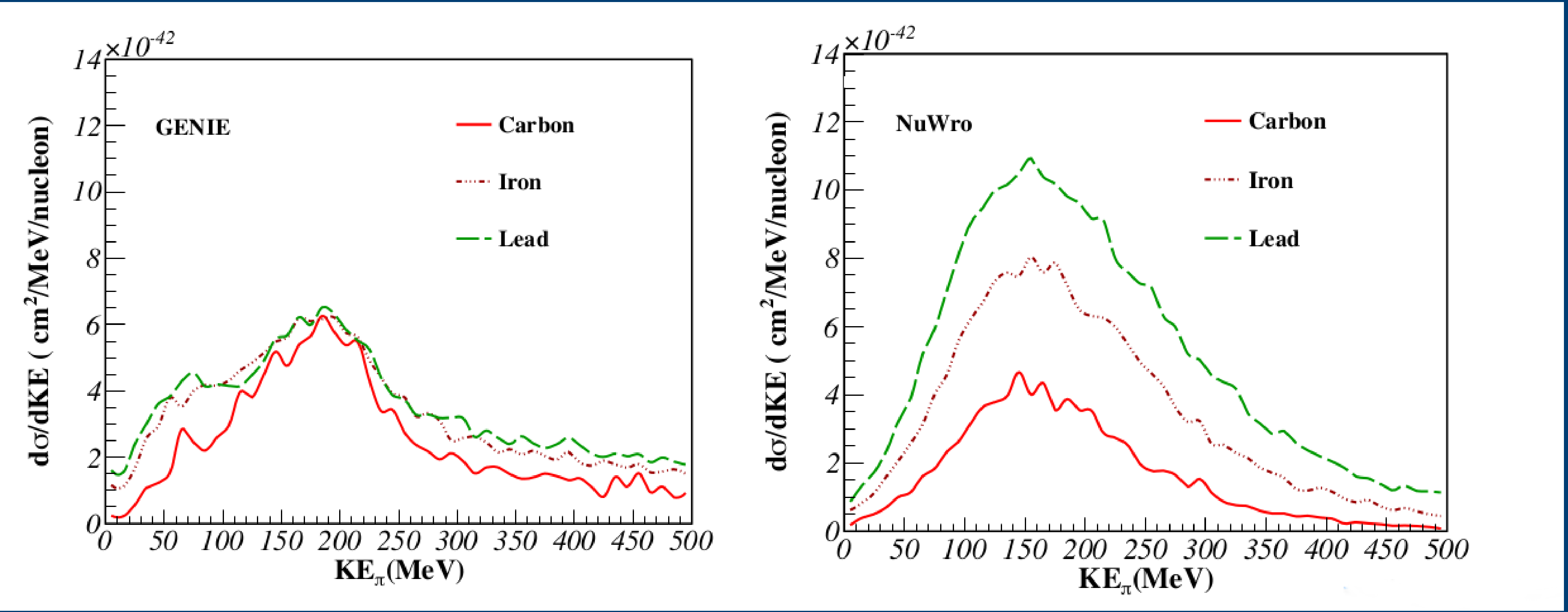




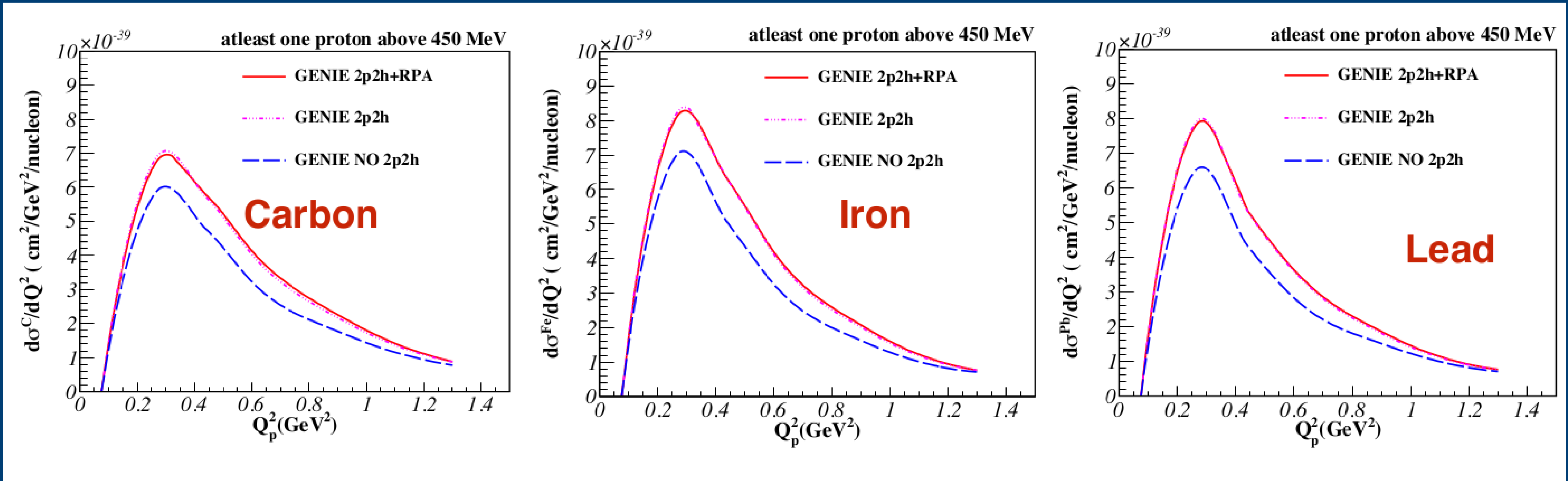
Phys. Rev. D 93, 112007 (2016)

A-dependence in GENIE and NuWro

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

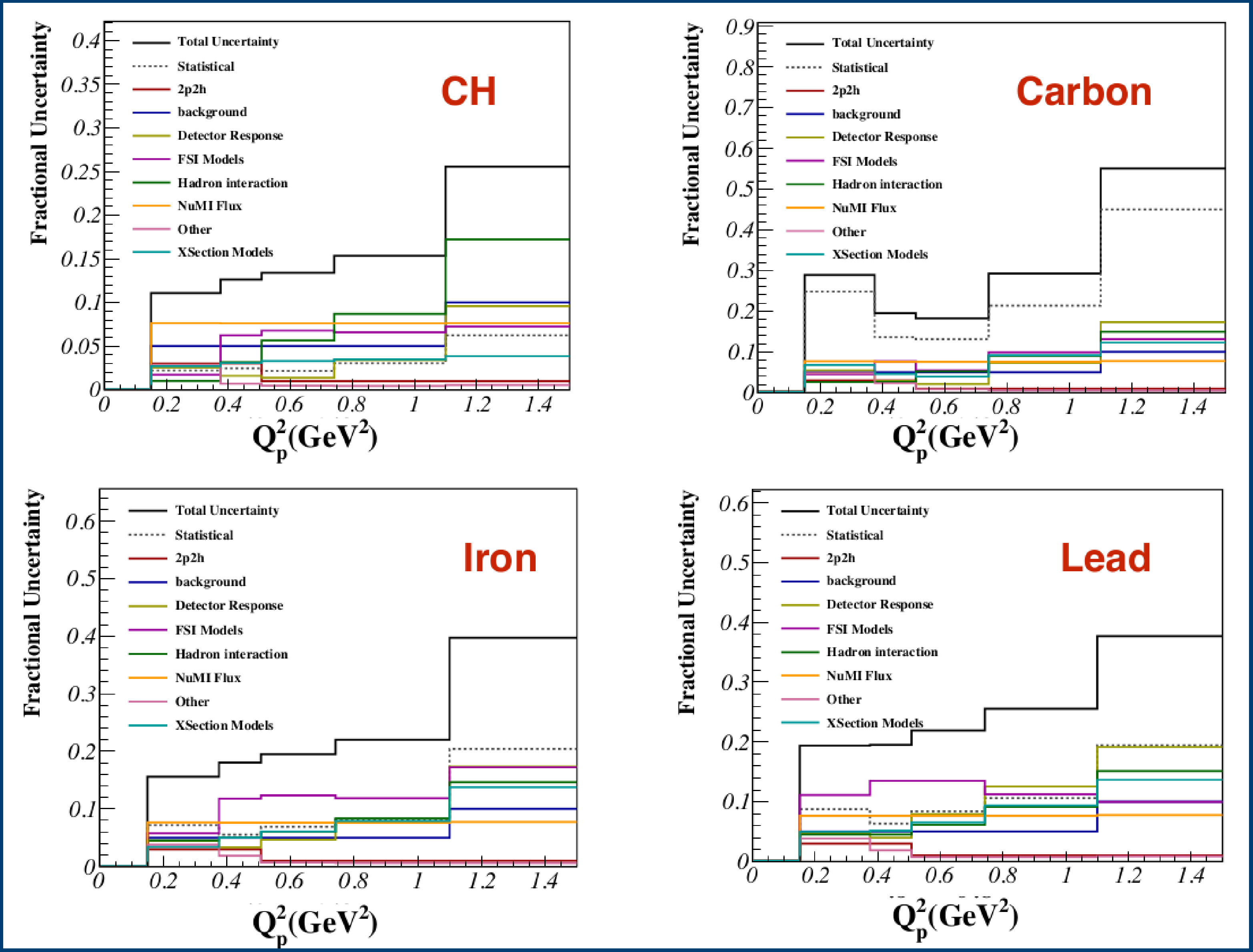


2p2h and RPA Comparisons

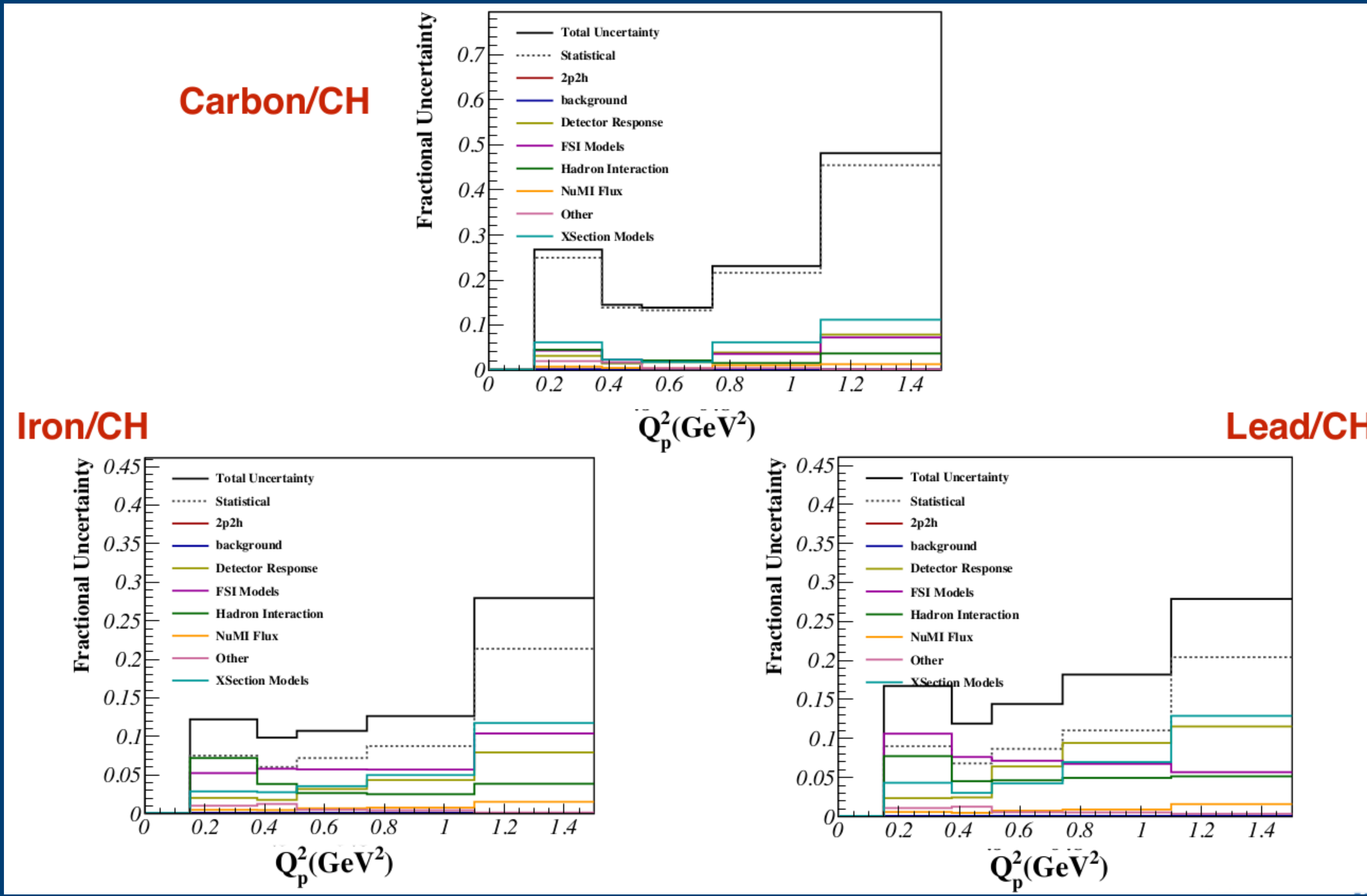


- This is solely to show effect of three different models: no 2p2h, 2p2h, and 2p2h + RPA
- Slight A dependence in the 2p2h model
- Small RPA suppression
  - Larger effect below the proton threshold (450 MeV)

Total Uncertainties



Ratio Uncertainties



Generators

- Table here explaining the difference
- GENIE (2.8.4)
  - M_A=0.99 GeV
  - Relativistic Fermi gas
  - Resonant pion production: Rein-Seghal
  - DIS (2003) Bodek Yang
  - Koba Nielsen Olsen & Pythia
  - Tuned 2p2h Valencia model
  - Non resonant tune
  - Geant 9.4.2
  - FSI has $A^{2/3}$ scaling