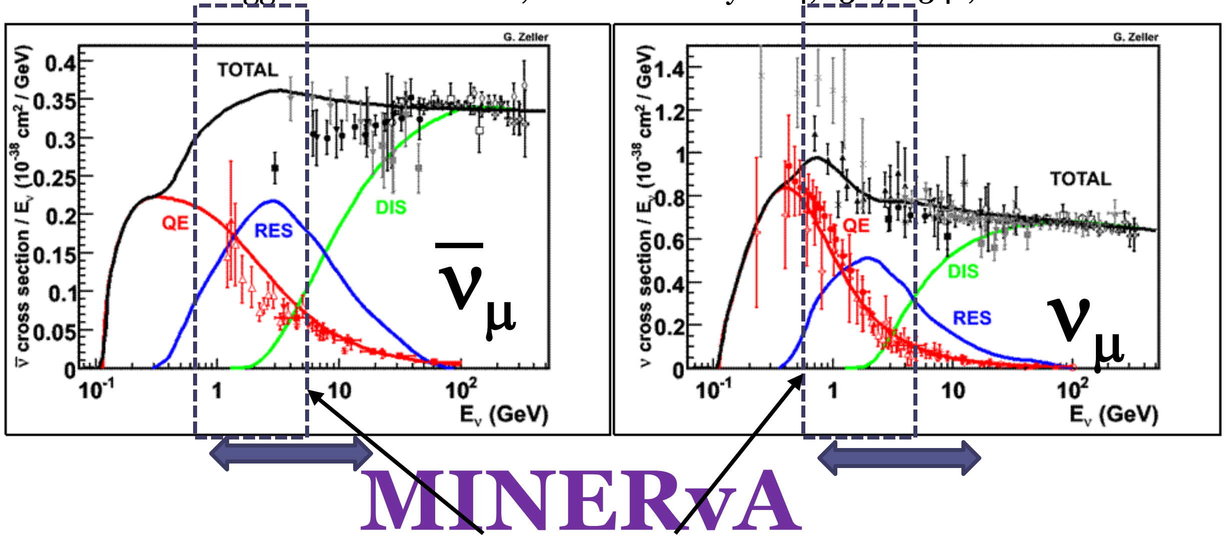
Muon Neutrino Charged Current Quasi Elastic Scattering in the MINERvA Experiment

Tammy Walton
New Perspectives Meeting
Hampton University
June 10-11, 2013

Outline

- Motivation
- Overview of the Analysis
- Conclusions

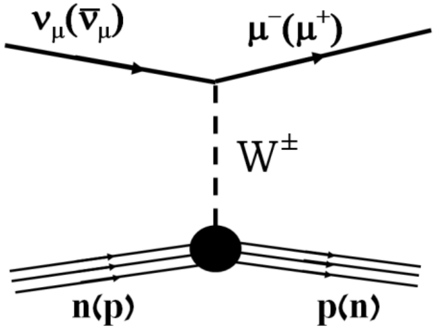
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



T2K, NOvA, LBNE, BooNEs

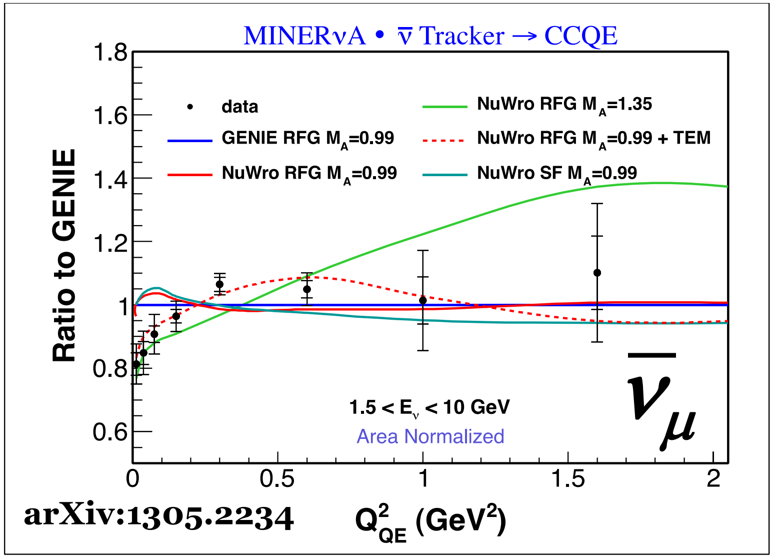
•Cross sections in the transition region from quasi-elastic to inelastic scattering have large uncertainties.

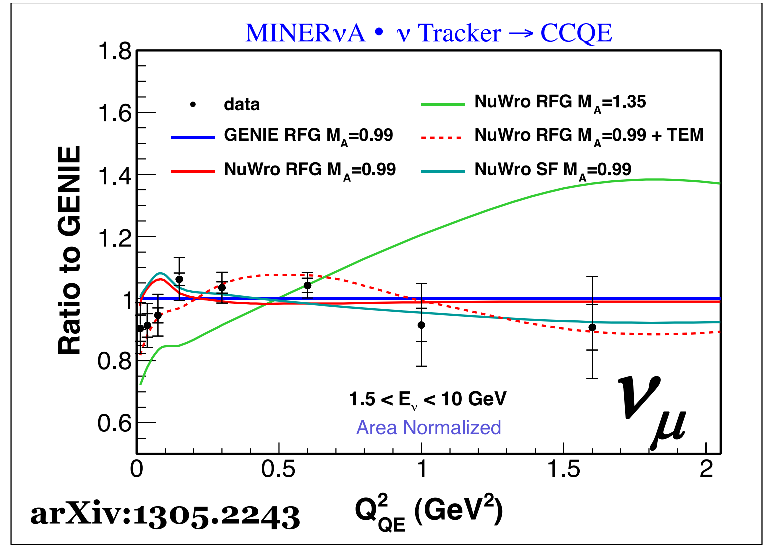
•Cross sections are one of the largest systematic uncertainties for neutrino oscillation experiments.



QE scattering considered a "standard candle" for oscillation experiments.

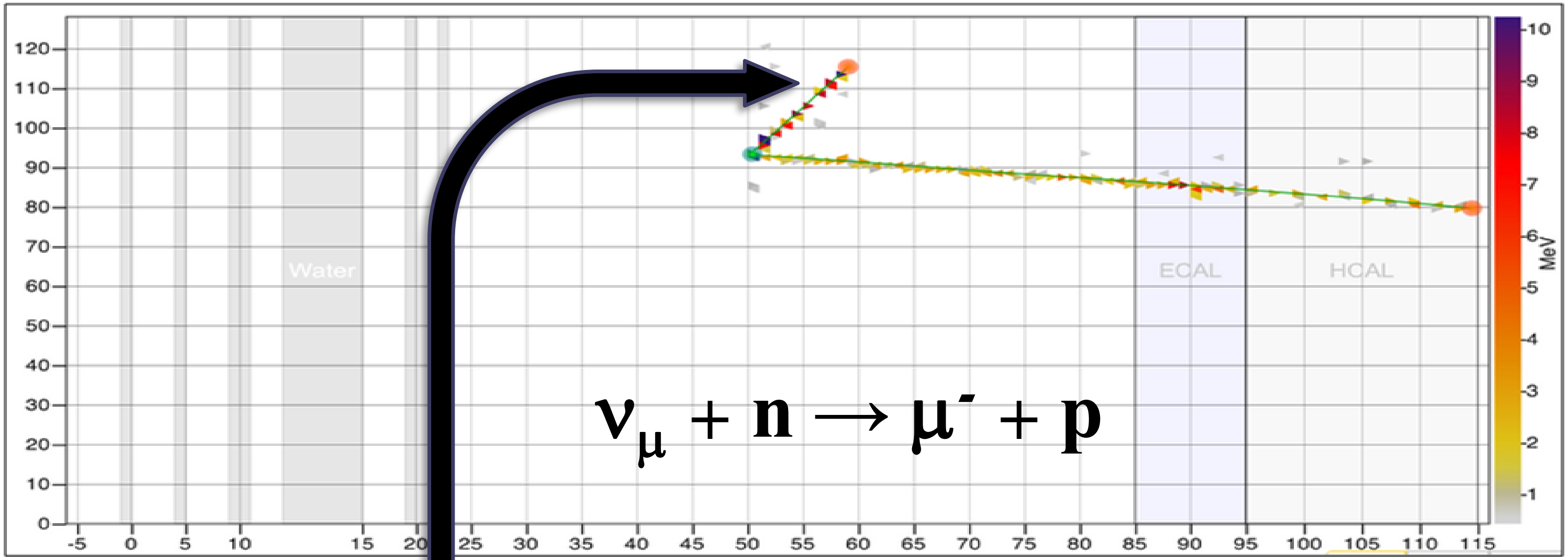
Celebrating MINERνA's First QE Results!





See Talk/Poster by Phillip Rodrigues/Cheryl Patrick

Expanding the ν_μ CC QE Program



$$\nu_\mu + n \longrightarrow \mu^- + p$$

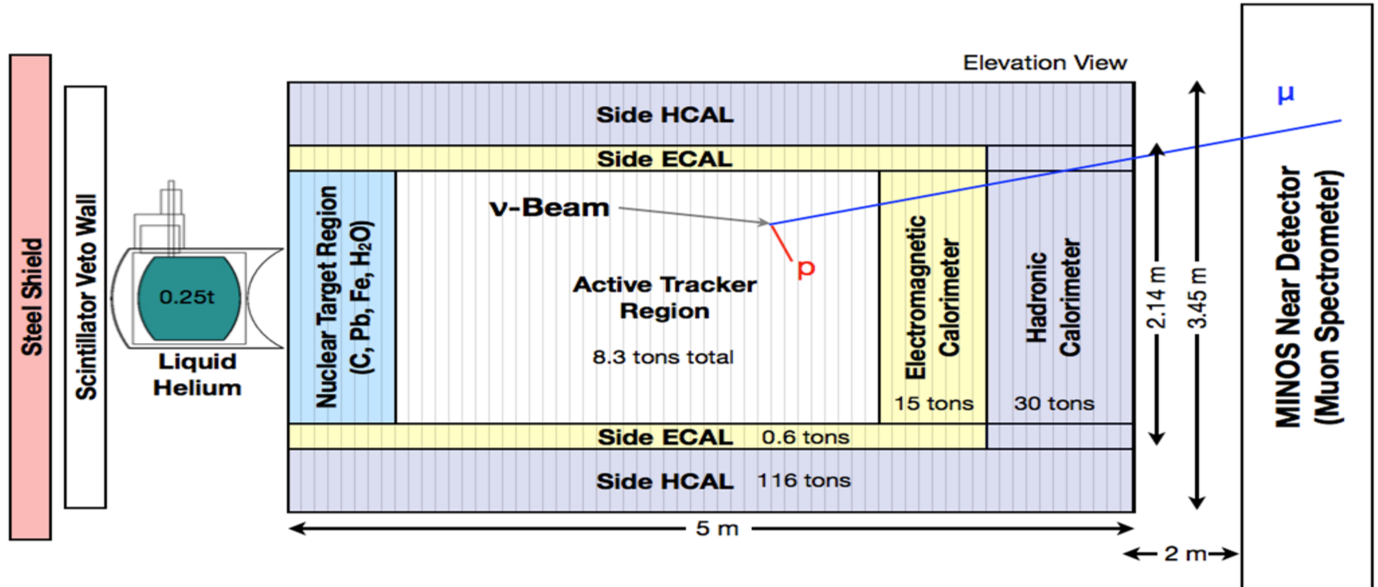
We can isolate and analyze the sample of CCQE candidates, where the proton is also tracked.

Introduces the 2-track ν_μ CCQE

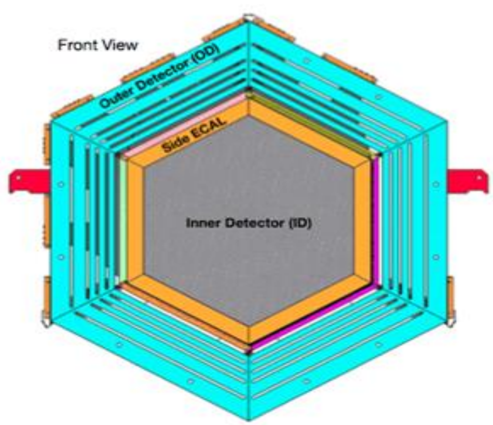
The MINERνA Detector

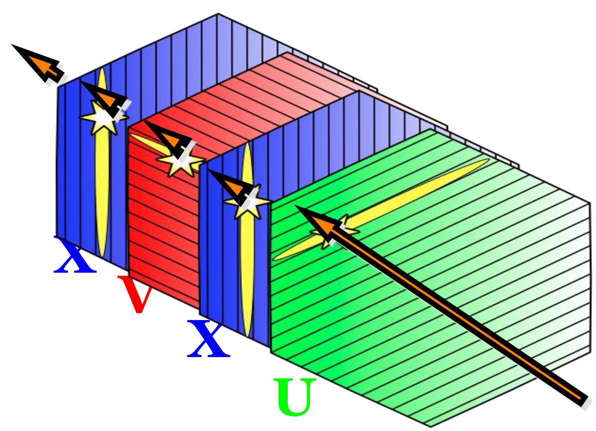
νs

See talk by Leonidas Aliaga on the NuMI flux



The MINERvA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).





Why a 2-track ν_μ CC QE Analysis?

- Cross check results with the 1-track ν_μ CC QE.
  - The 1-track and 2-track analyses reconstruct the recoil system differently.
  - Different event selections, efficiencies, purities, and hadron uncertainties.
- Reconstruct kinematics from both the final state muon and proton.
  - Study final state interactions.
- The 2-track analysis accepts muons that are not captured or tracked by MINOS.
  - Broader muon scattering angle acceptance.
- Reconstruct the vertex in the nuclear targets.
  - Reduces the background coming from the neutrino interactions on the (CH) tracker's modules adjacent to the nuclear target.

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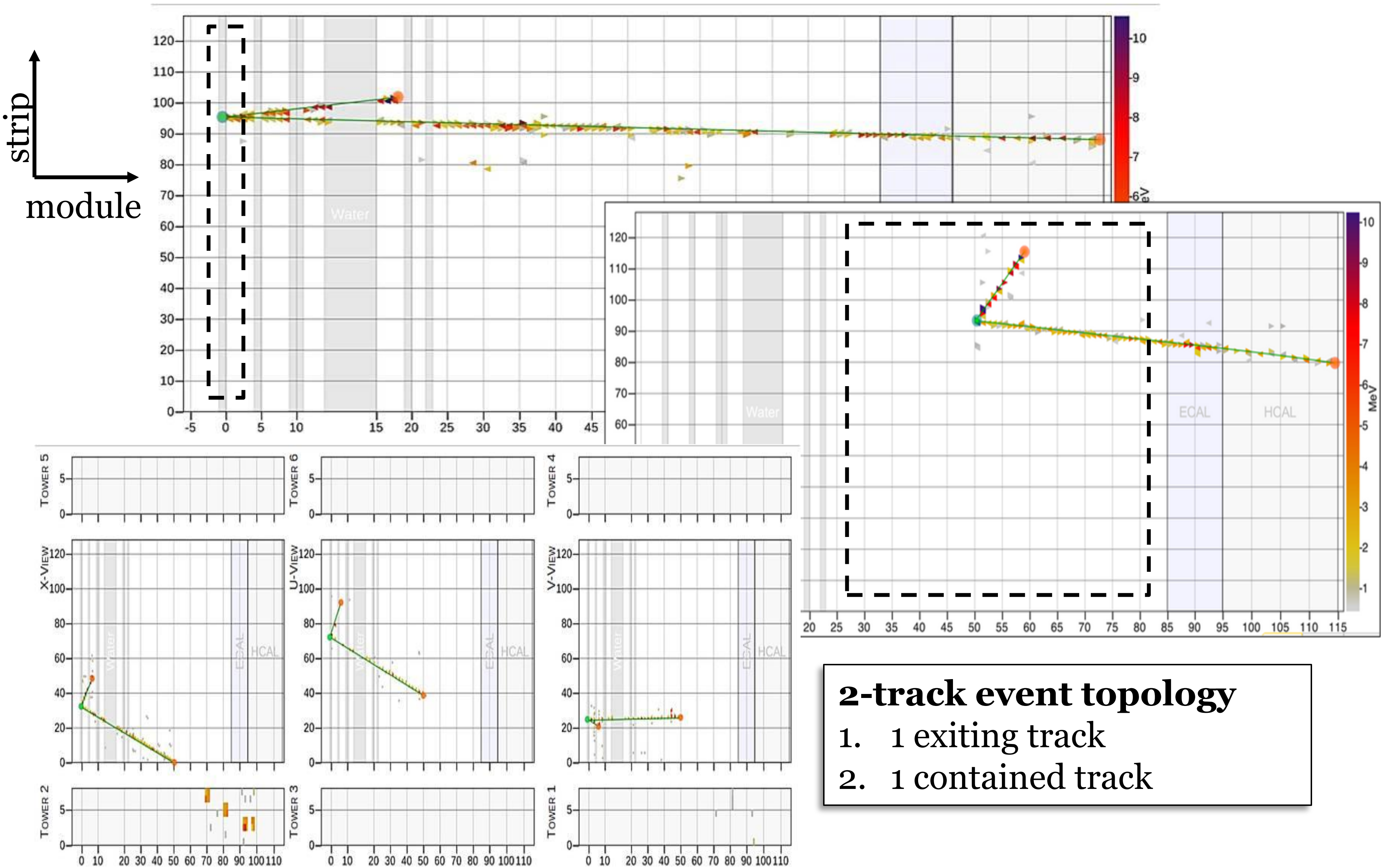
Reconstructing the 2-track Events



2-track event topology

1. 1 exiting track
2. 1 contained track

Reconstructing the 2-track Events

2-track event topology

1. 1 exiting track
2. 1 contained track

Defining the ν_μ CC QE Signal

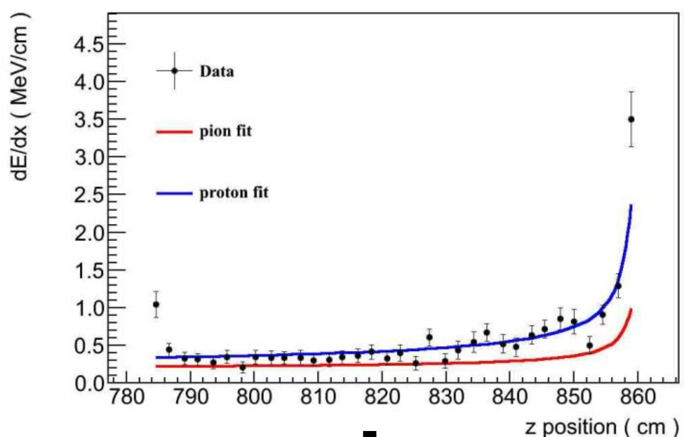
- The neutrino event generator (GENIE) defined CCQE

or

- QE-like
  - 1 final state muon
  - 1 final state trackable nucleon
    - Trackable is defined as a nucleon with kinetic energy ≥ 150 MeV
    - N nucleons with kinetic energy < 150 MeV are allowed.

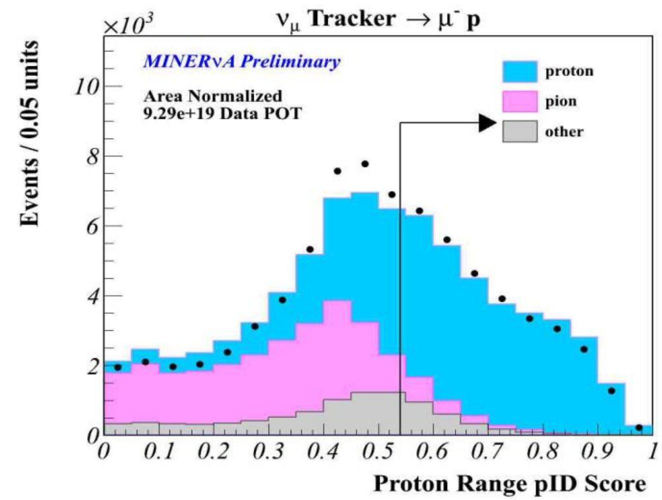
Selecting the ν_μ CC QE Candidates

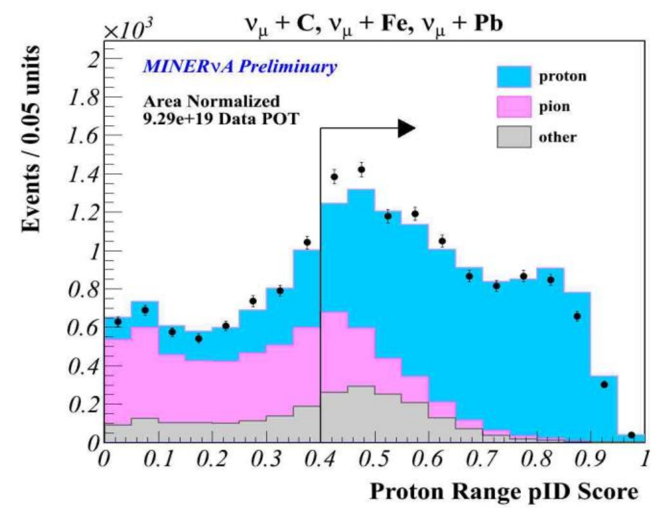
Fit the measured dE/dx profile of the hadron's track to the proton and pion calculated dE/dx profiles of various momentum.



$$\text{score}_{\text{proton}} = 1.0 - \frac{\left(\chi^2/\text{ndf}\right)_{\text{proton}}}{\sqrt{\left(\chi^2/\text{ndf}\right)^2_{\text{proton}} + \left(\chi^2/\text{ndf}\right)^2_{\text{pion}}}}$$

<u>Cut 1:</u>
Requires the hadron's track candidate to resemble a ranging out proton.



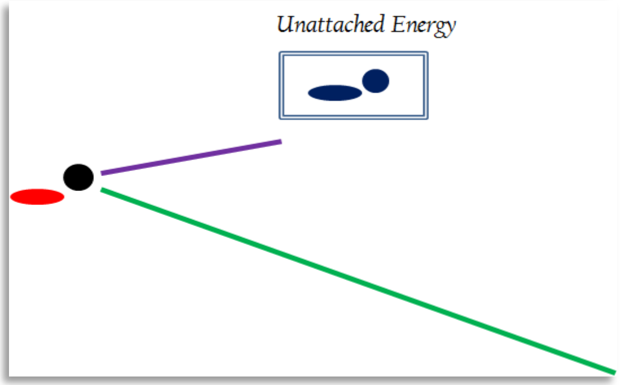


Selecting the ν_μ CC QE Candidates

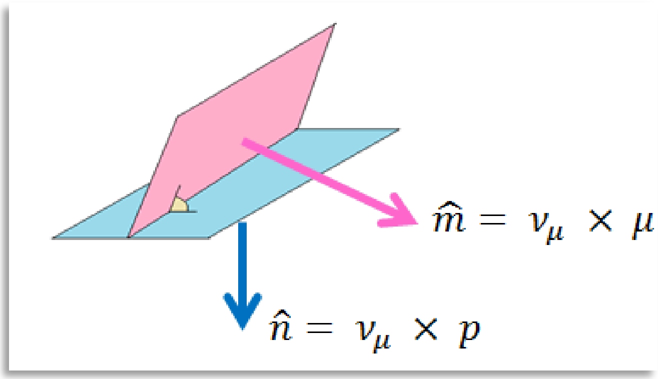
Cut2: isolate the CCQE-like events

- To optimize the efficiency and purity, we use a multivariate analysis for selecting the 2-track CCQE-like candidates.
- The 2-track events have the pID range score cut applied.
- The applied multivariate classifier is the kNN.
- The training variables are:
  - **Unattached energy:** energy that is unassociated with a track or vertex in the event.
  - **Co-planarity angle:** angle between the ν_μ–μ and ν_μ–p planes.

Unattached Energy



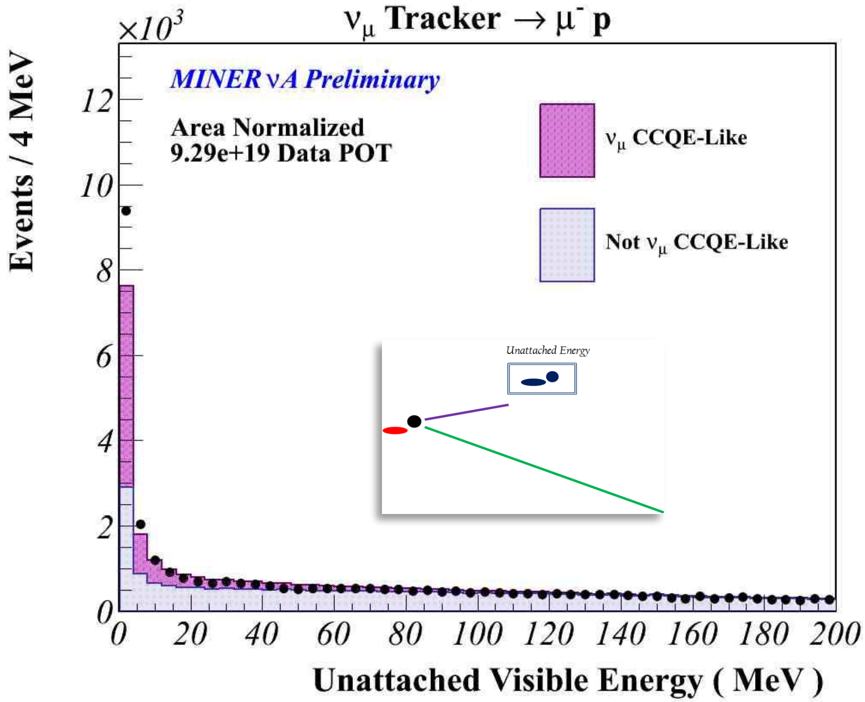
Co-planarity Angle

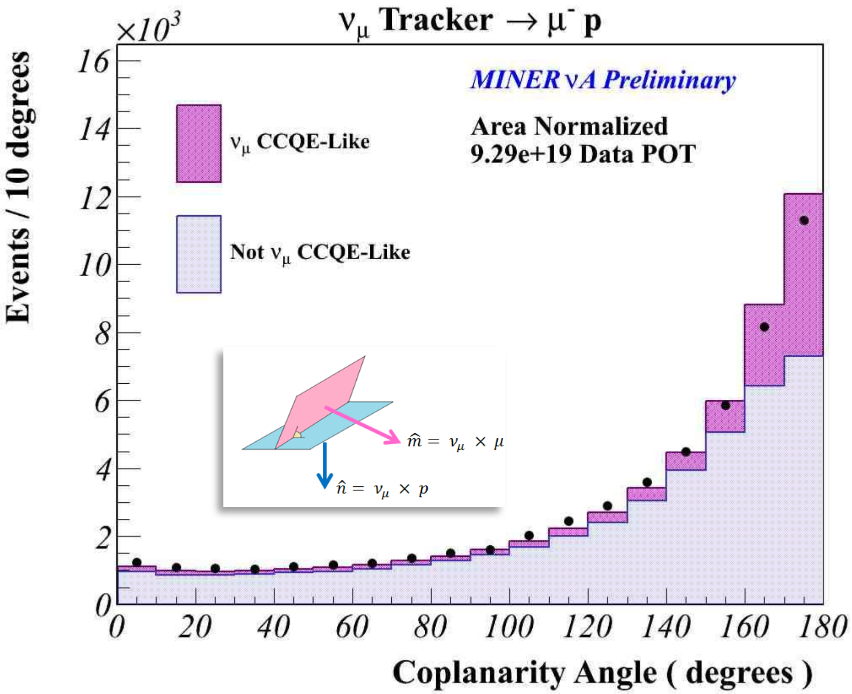


Selecting the ν_μ CC QE Candidates

Cut 2:
Requires the event to look CCQE-like.

The input multivariate analysis variables for the events reconstructed in the **tracker region.**





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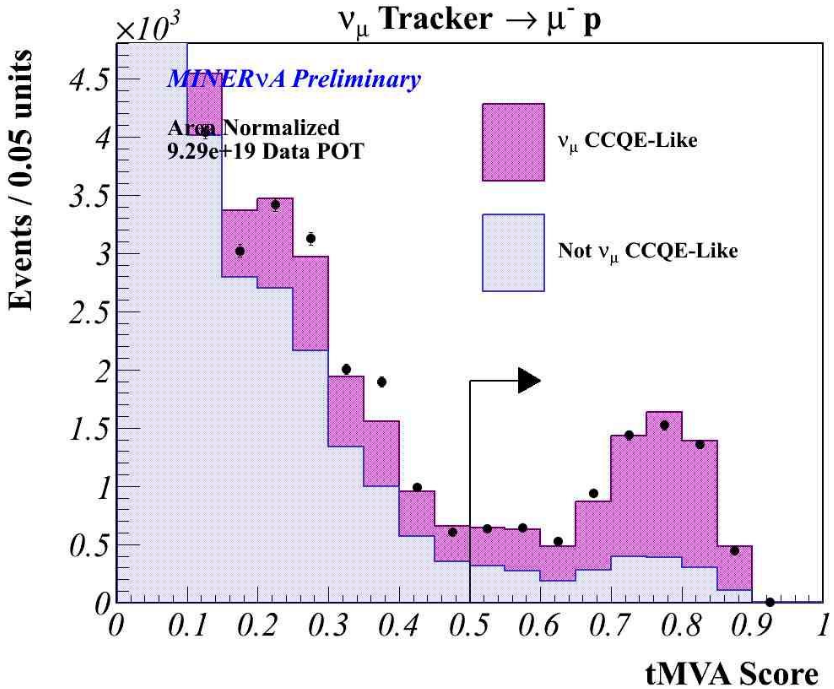
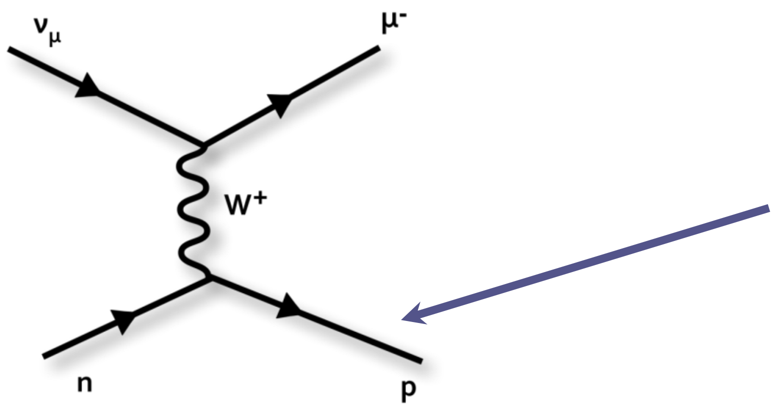


The tMVA (**t**oolkit for **m**ulti**v**ariate **a**nalysis) score is a powerful discriminate for separating the 2-track CCQE-like signal and background events.

Reminder: uses the kNN multivariate classifier to select the signal.

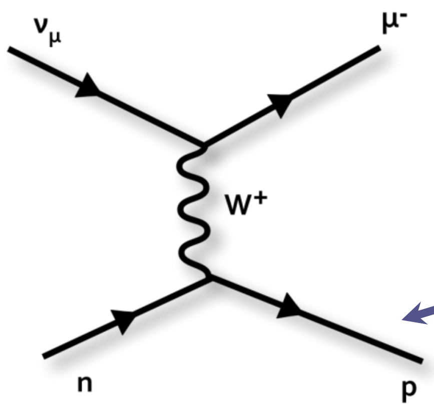
Now let's take a snapshot of the 2-track ν_μ CCQE analysis

The advantage of the 2-track CCQE: reconstruct the 4-momentum of the μ^- and p



Assumption:
Scattering off of a free nucleon

The advantage of the 2-track CCQE: reconstruct the 4-momentum of the μ^- and p



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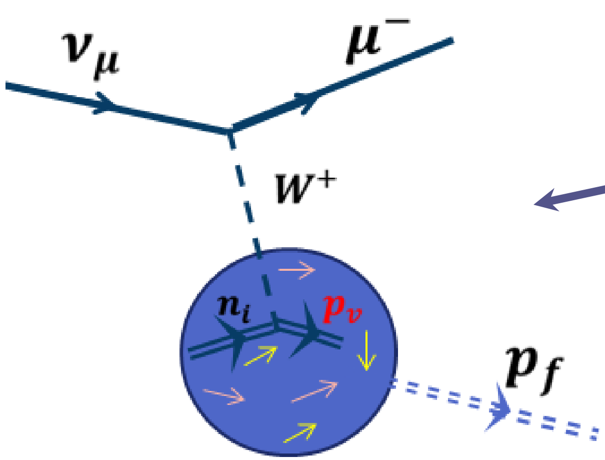
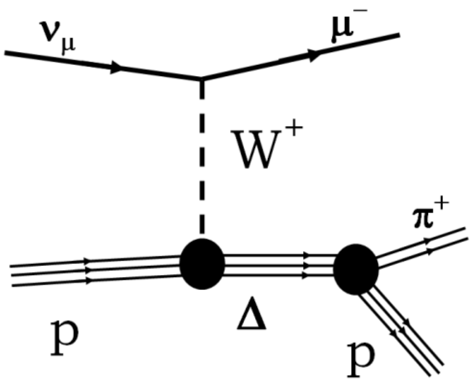


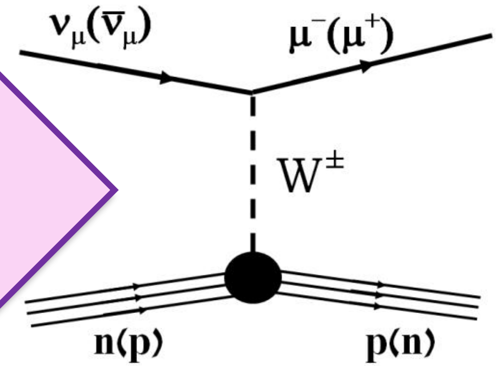
Reality:
Scattering off of a bound particle in a nuclear medium

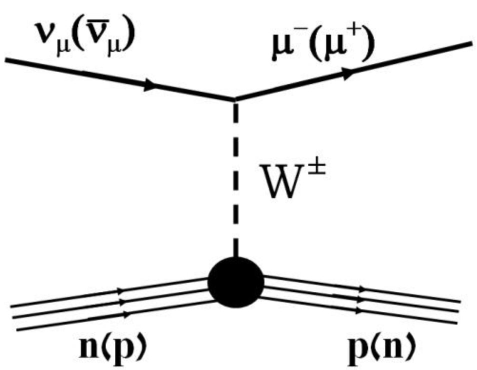
Study final state interactions.

Study final state interactions.

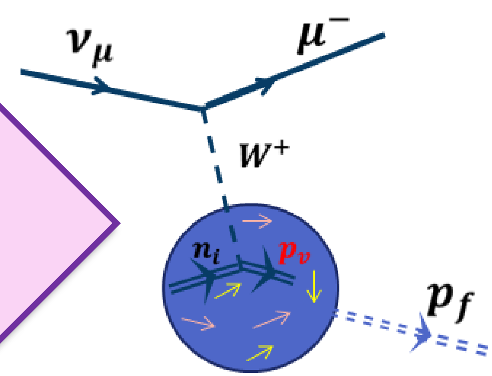


Pions absorbed in the nucleus or in the passive materials can mimic the CCQE signal.

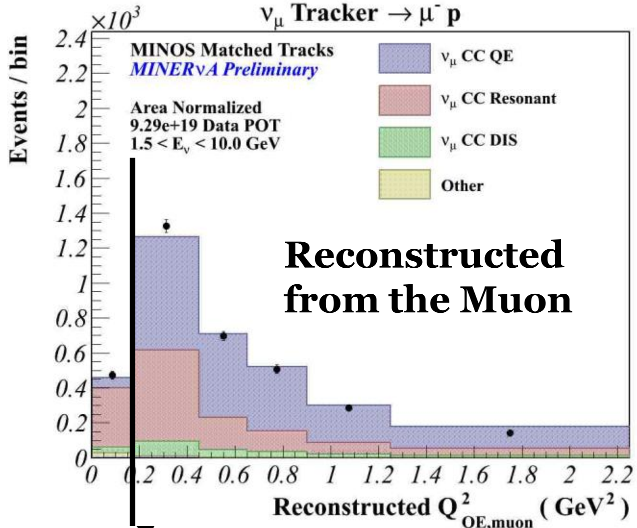


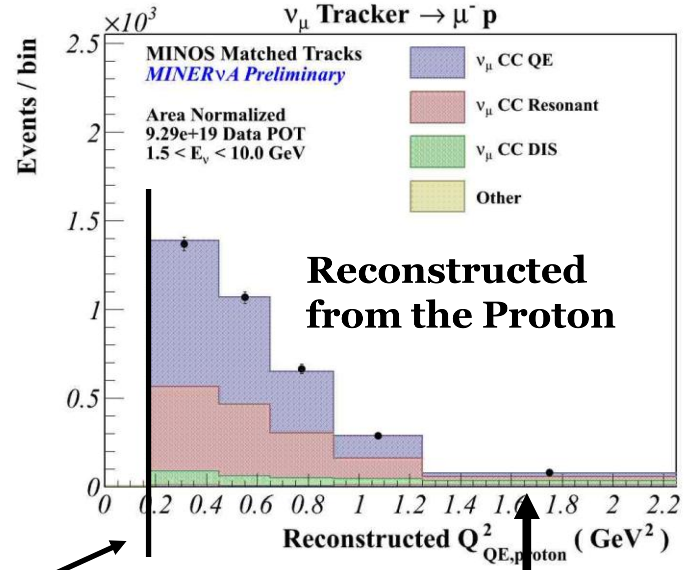


Proton re-interacts in the nucleus → proton's momentum and angle at the interaction vertex are not the same as when it exits the nucleus.



Reconstructing Kinematics from both the Muon and Proton



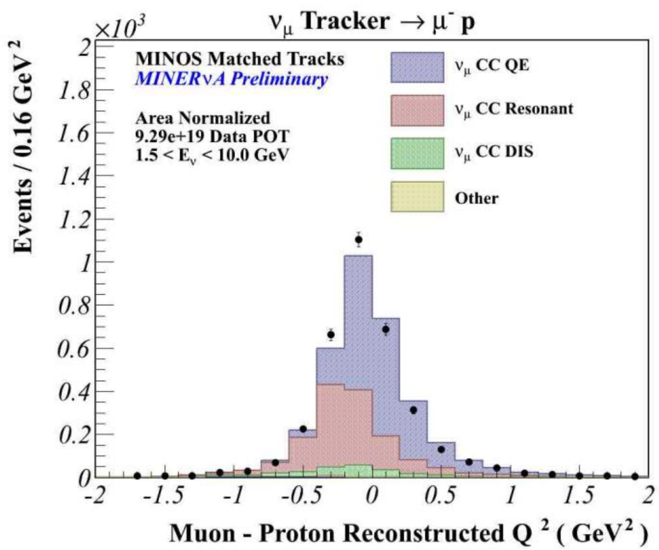


Tracking threshold

<u>High Q² mis-reconstruction</u>

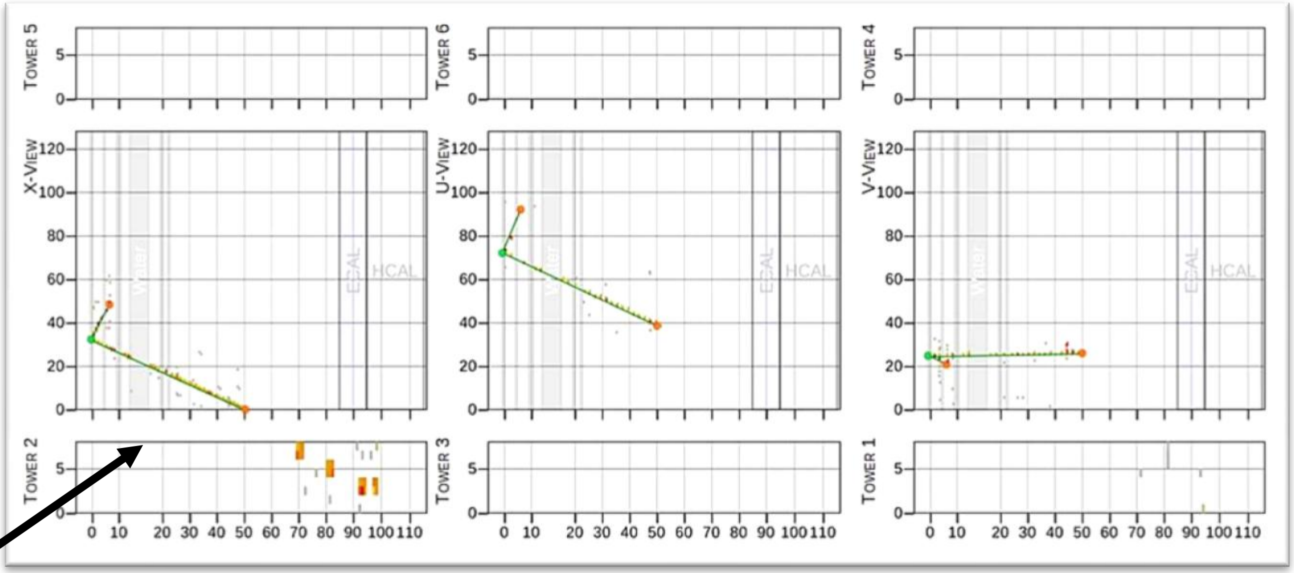
- Protons are ranging out in the downstream electromagnetic calorimetry → energy loss due to electromagnetic interactions are not accounted for.

- Proton changes into a neutron.

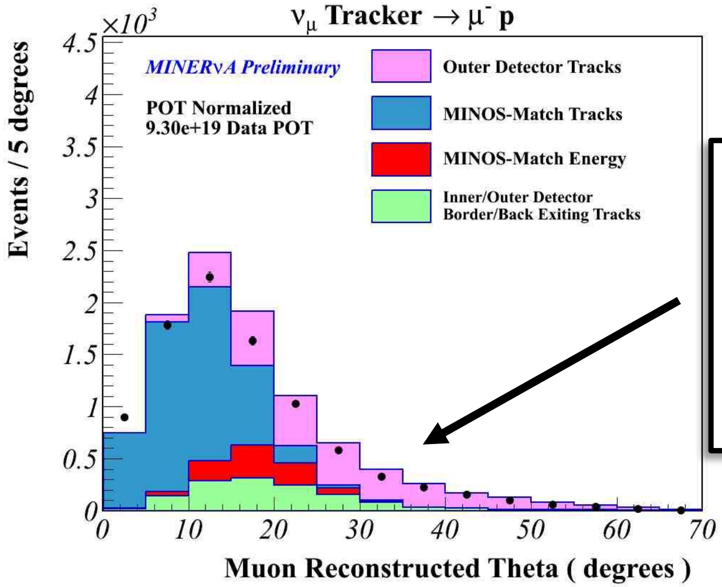


Next to come: Isolate events with controlled sample of ranging out protons.

Expanding the Muon Angular Acceptance



- Events with various muon reconstructed topologies are accepted.
- Expanding the acceptance is very important for the nuclear targets region event reconstruction.



- Poor muon energy resolution.
- Reconstruct Q^2 from the proton.

Conclusions

- There are many advantages to the 2-track analysis.
  - Reconstruct kinematics from the proton's arm.
  - Study final state interactions.
  - Reconstruct events with a broader muon's angle acceptance.

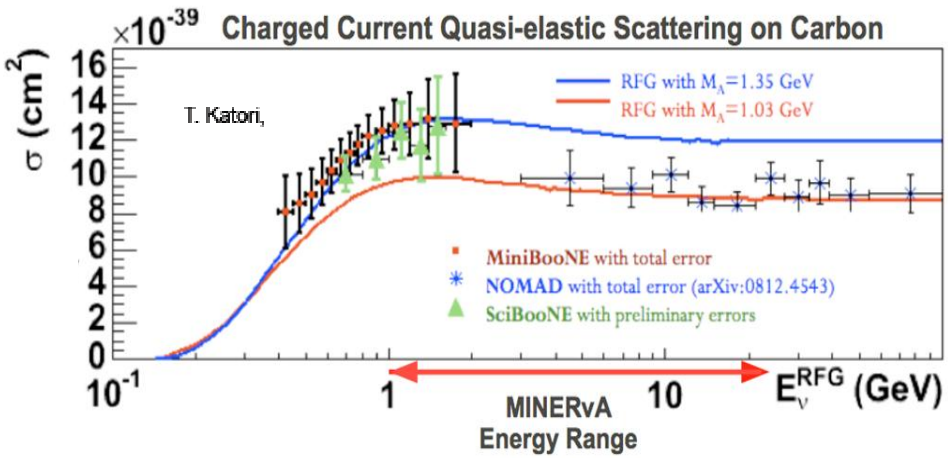
- We will measured the 2-track CCQE cross sections on the hydrocarbon, pure carbon, iron, and lead targets.
  - Results will be complimentary to our 1-track ν_μ CCQE analysis.
  - Contribute to the understanding of the hadron propagation in the nucleus.
  - Study the A-dependence of the neutrino interaction (understand nuclear effects for heavier nuclei).

- Stay tuned for more exciting results from the CCQE program in MINERvA.

Back-up Slides

Recent Measurements of the Axial Mass

Experiment	Target	Cut in Q^2 [GeV^2]	M_A[GeV]
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

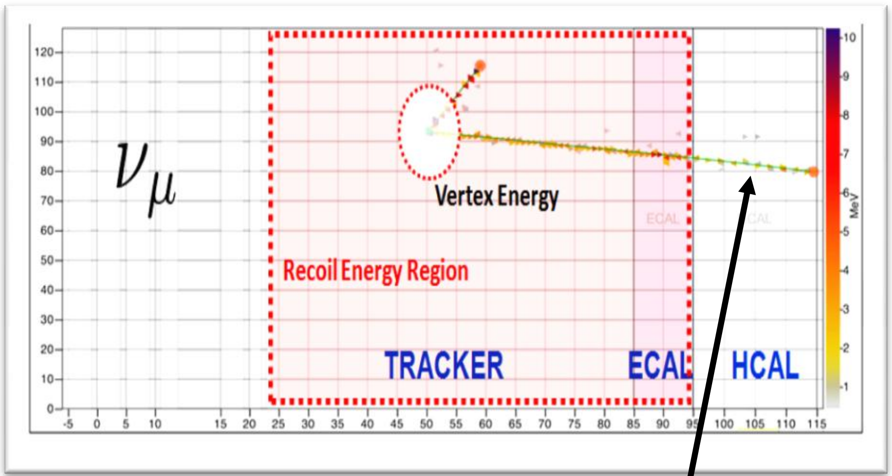


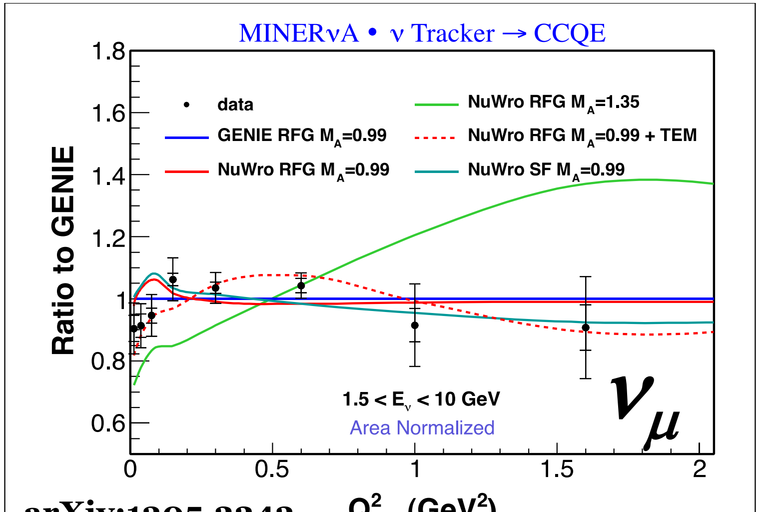
Low energy neutrino data prefer a higher value of M_A.

High energy neutrino data prefer a low value of M_A, which is consistent with the bubble chamber measurements.

The recent measurements are all on heavy nuclei, whereas the previous measurements mainly were extracted from the bubble chamber ^{2}H filled experiments.

CCQE Candidate





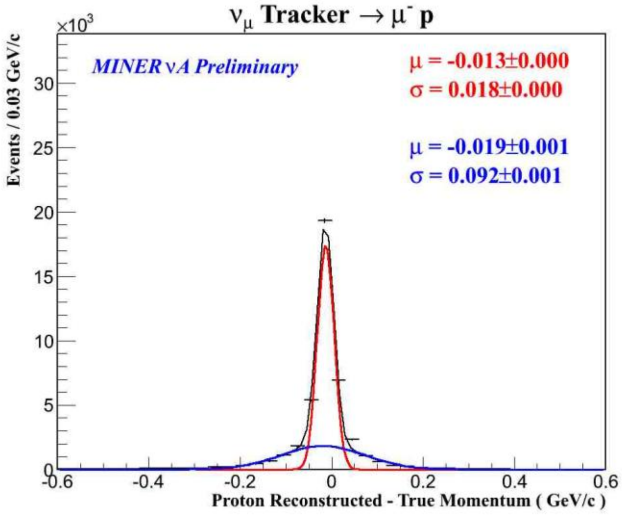
arXiv:1305.2243

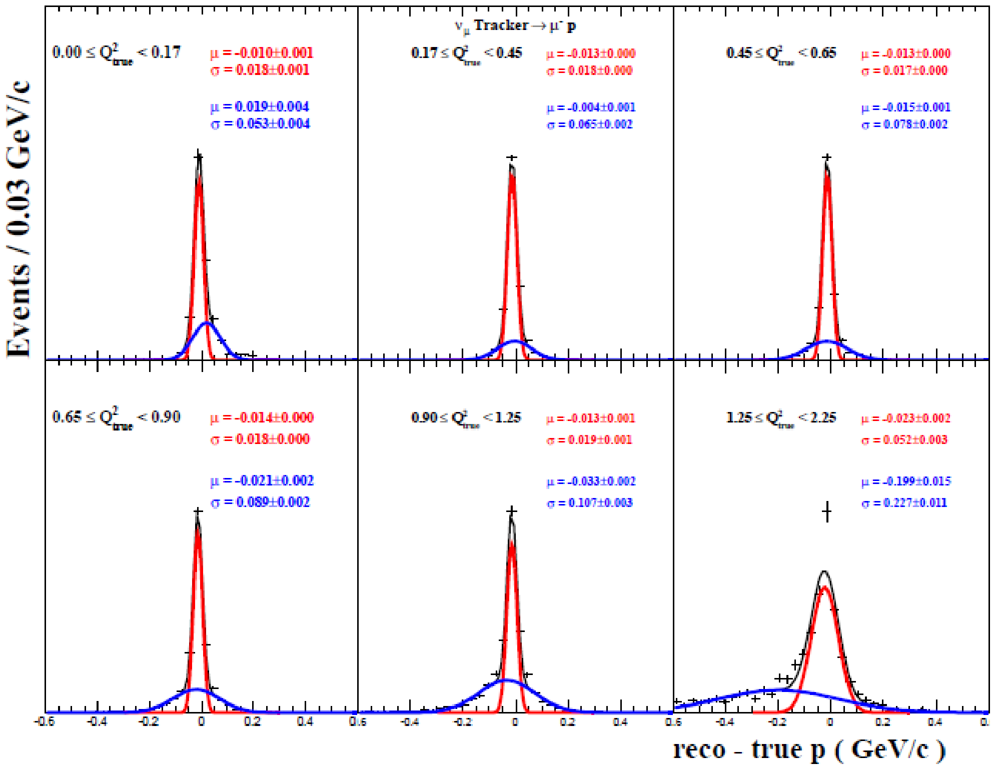
The muon is tracked by MINOS

Event Selection

1. Negative Charged Analyzed Muon → muon is tracked and matched by MINOS.
2. Reconstruct a sphere (radius = 30 cm) around the vertex. The spherical region contains 225 MeV kinetic energy protons and 100 MeV kinetic energy pions.
3. Q^2 dependent cut on the recoil energy and the recoil energy excludes energy in the vertex spherical region.

Proton Energy Reconstruction

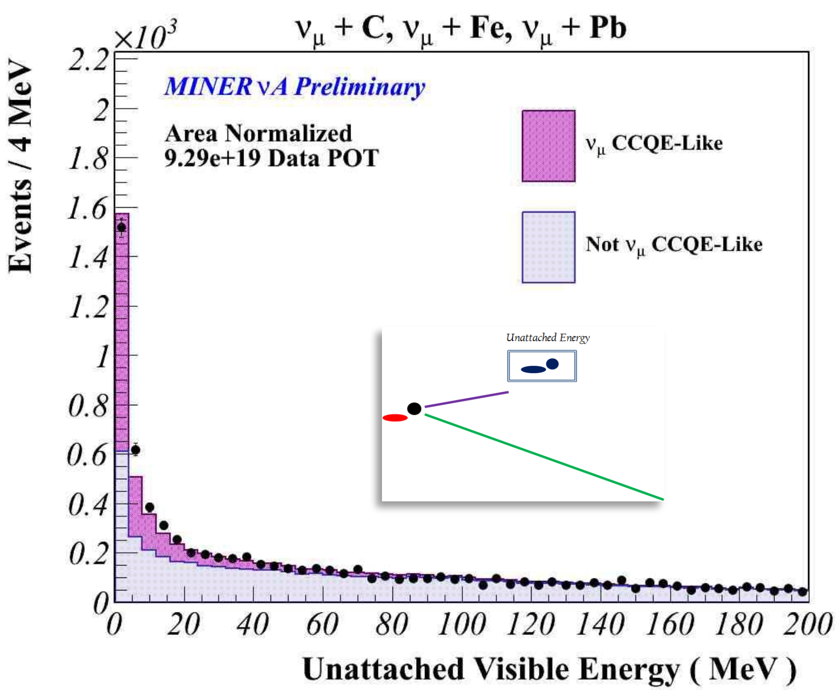


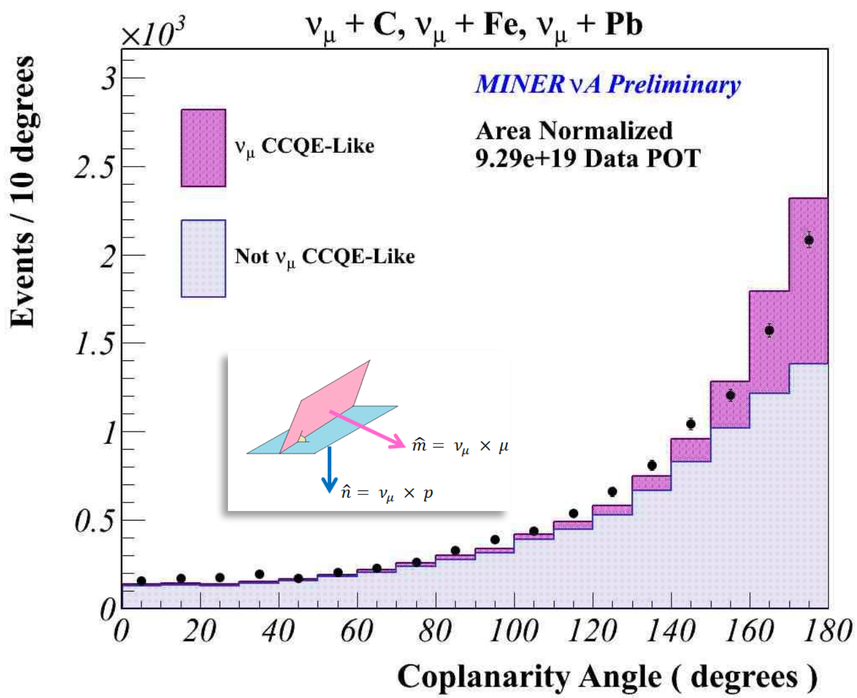


Selecting the ν_μ CC QE Candidates

Cut 2:
Requires the event to look CCQE-like.

The input multivariate analysis variables for the events reconstructed in the **nuclear targets region**.





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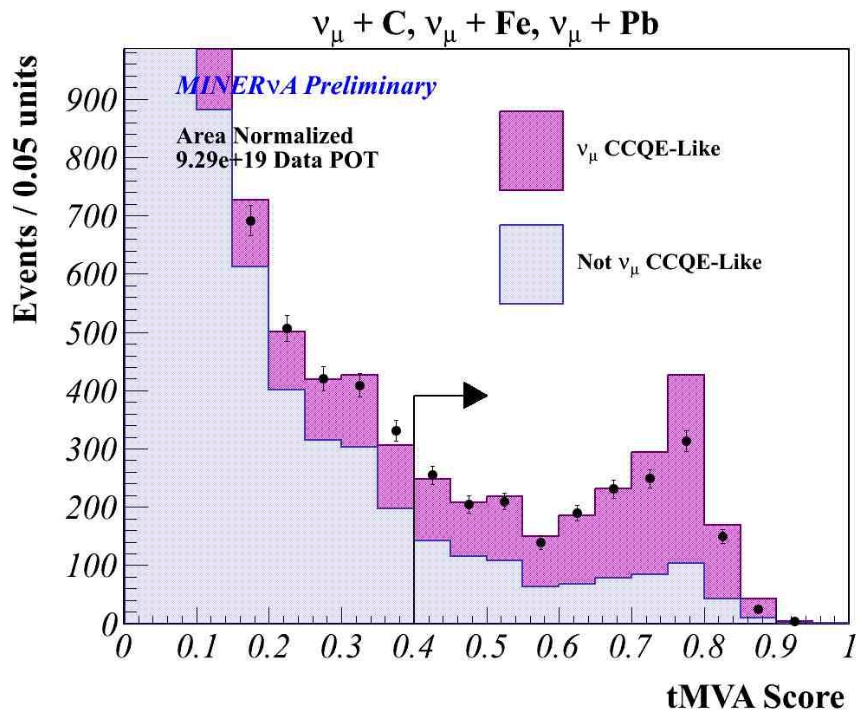

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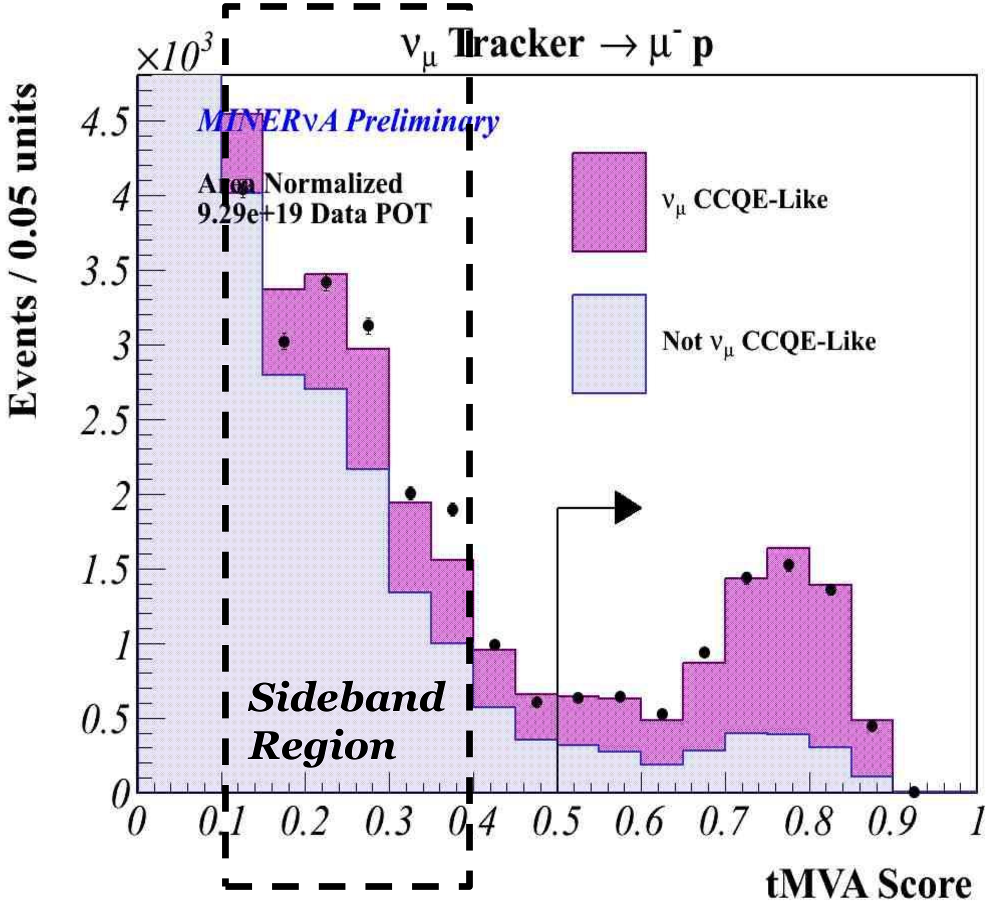
Reminder: uses the kNN multivariate classifier to select the signal.

Constraining the non QE-like Backgrounds



Use the sideband technique to constrain the background.

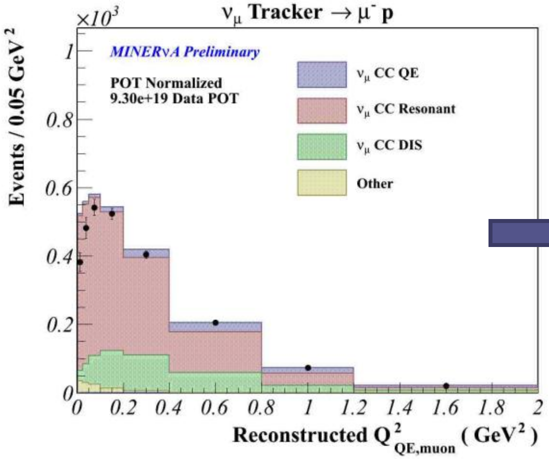
For the MINOS matched sample, the sideband region only includes the events with a MINOS matched track.

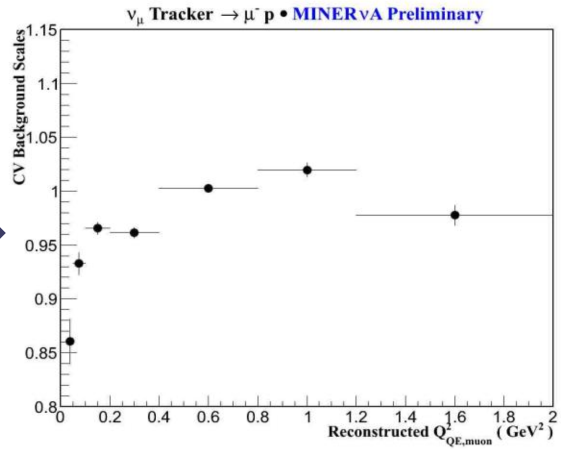
The tMVA score is independent of the Q^2 reconstructed from the muon's or proton's kinematics.

Procedure:

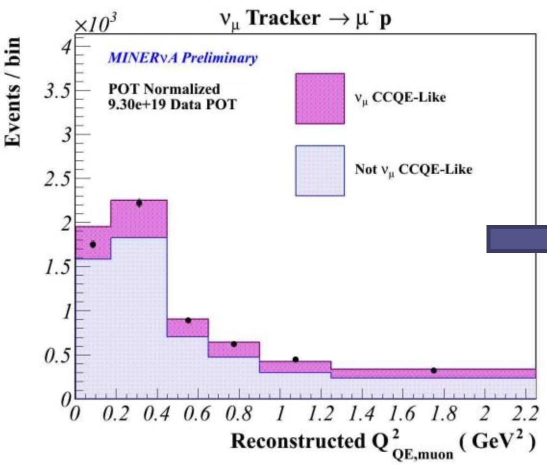
Scaled the background in the sideband region such that the data and Monte Carlo matches perfectly, thus extracting the background scale factors.

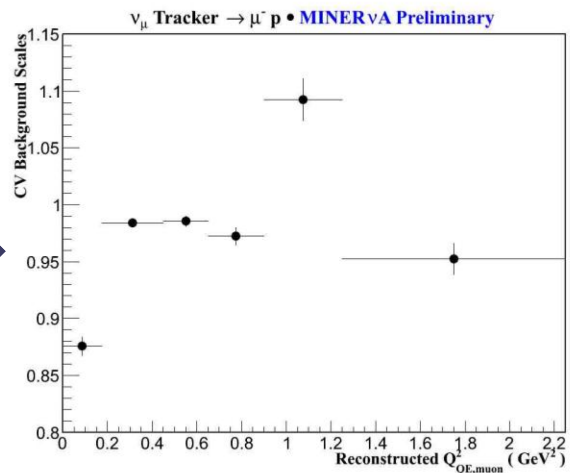
See next slide.



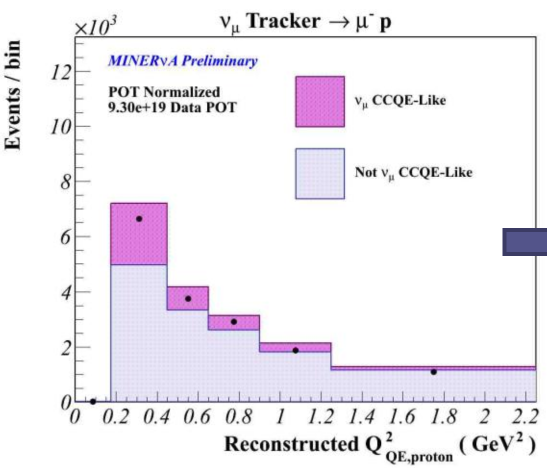


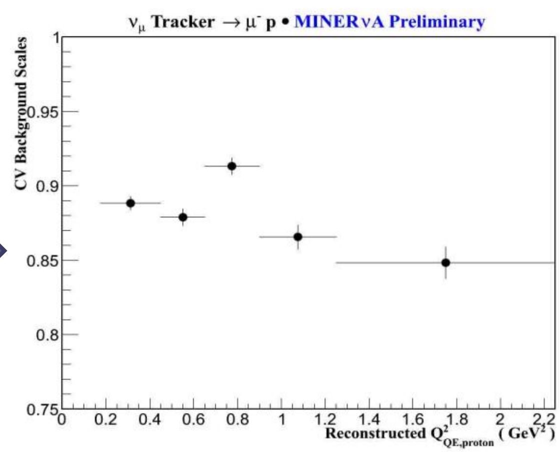
MINOS matched sample for comparing with the 1-track analysis. The signal and backgrounds are defined by the GENIE.





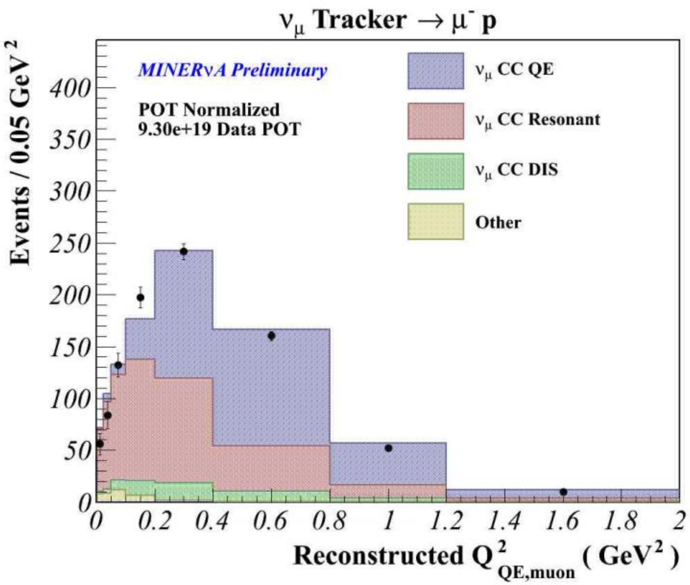
MINOS matched sample for studying final state interactions. The signal and backgrounds are defined by the 2-track QE-like.



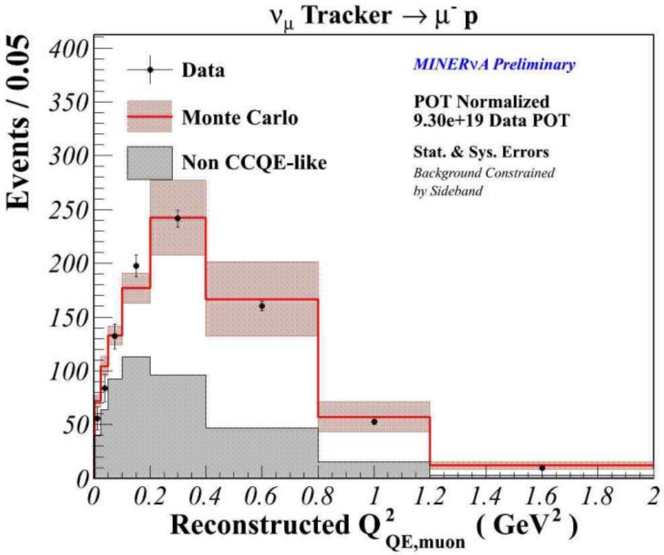


The all muons sample. The signal and backgrounds are defined by the 2-track QE-like.

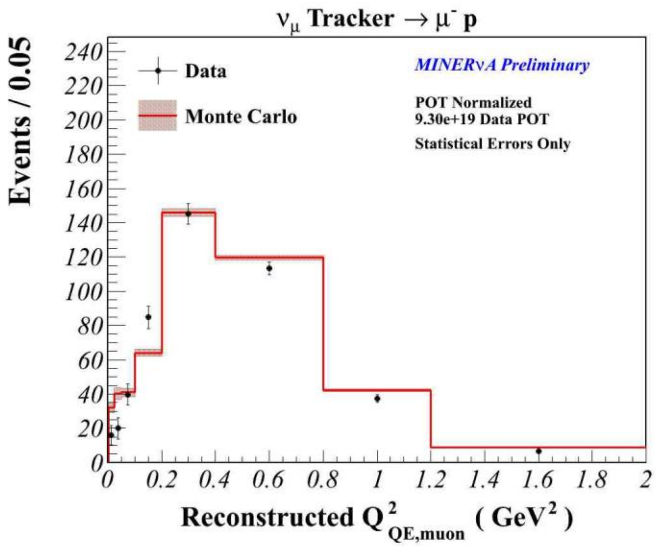
Cross Checking Results with the 1-track ν_μ CC QE



Constrain the background



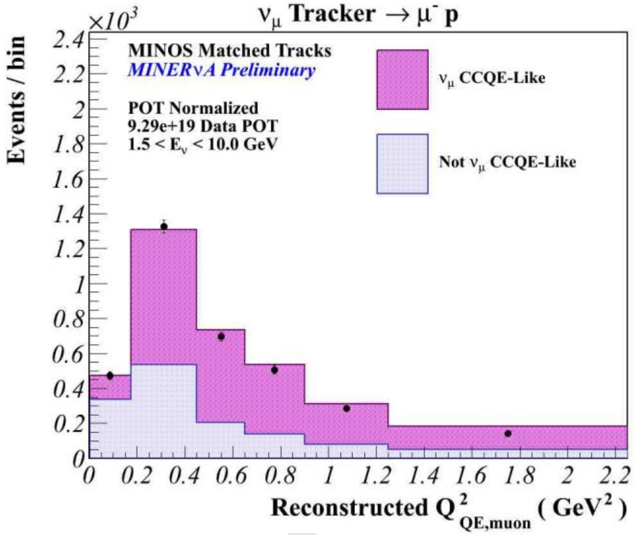
Subtract the background

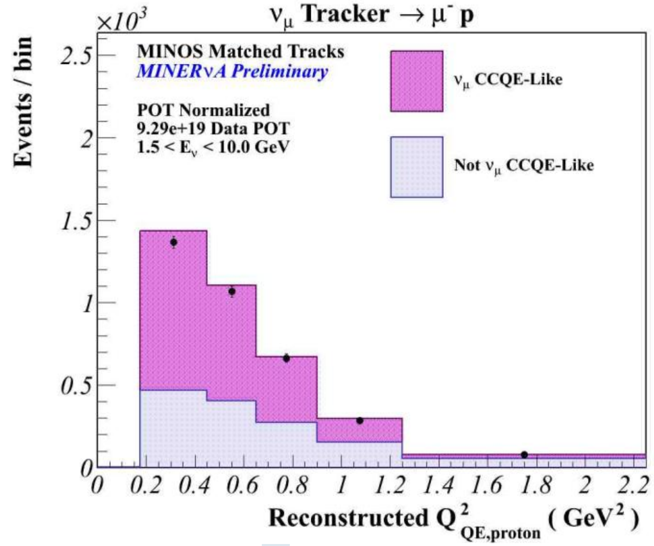


<u>Next steps:</u>

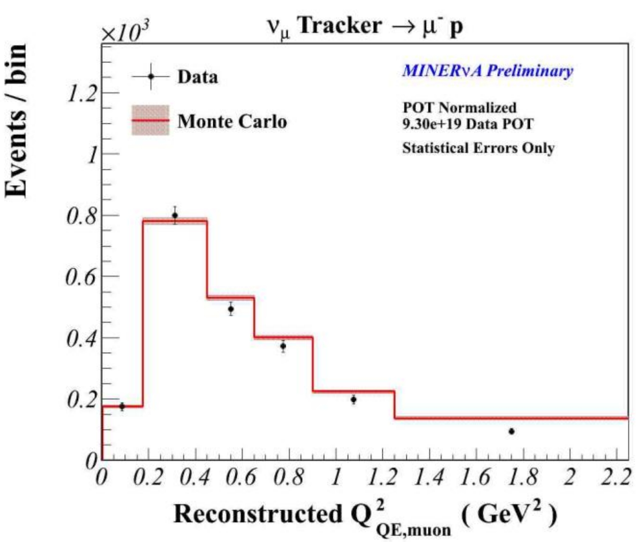
1. Unfolding (see talk by Kenyi Hurtado).
2. Normalized by the Efficiency.
3. Integrated the NuMI flux → Cross section.
4. Compare with the 1-track measurement.
5. Include the full data set.

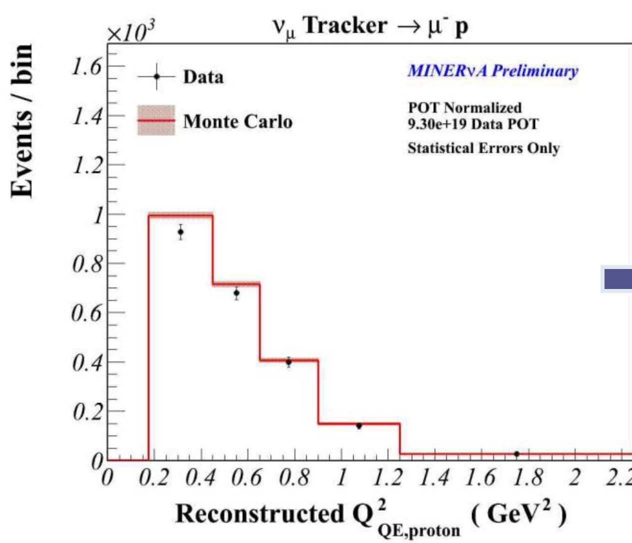
Reconstructing Kinematics from both the Muon and Proton





Constrain and subtract the background

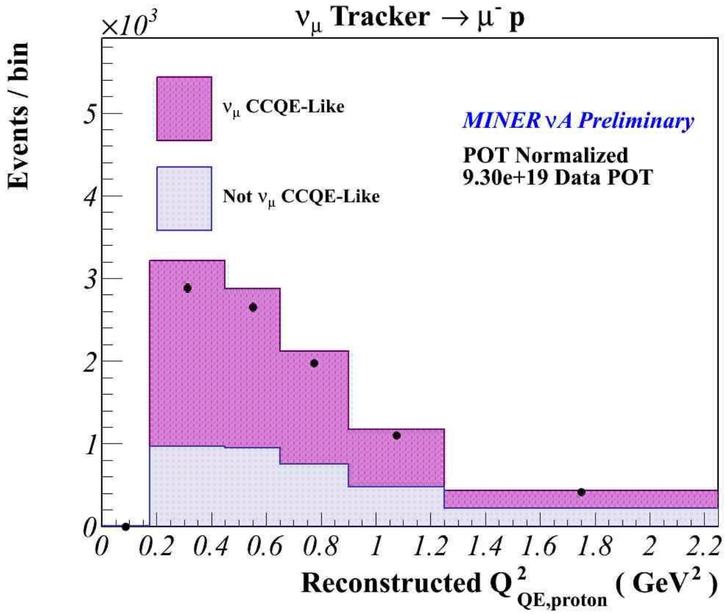




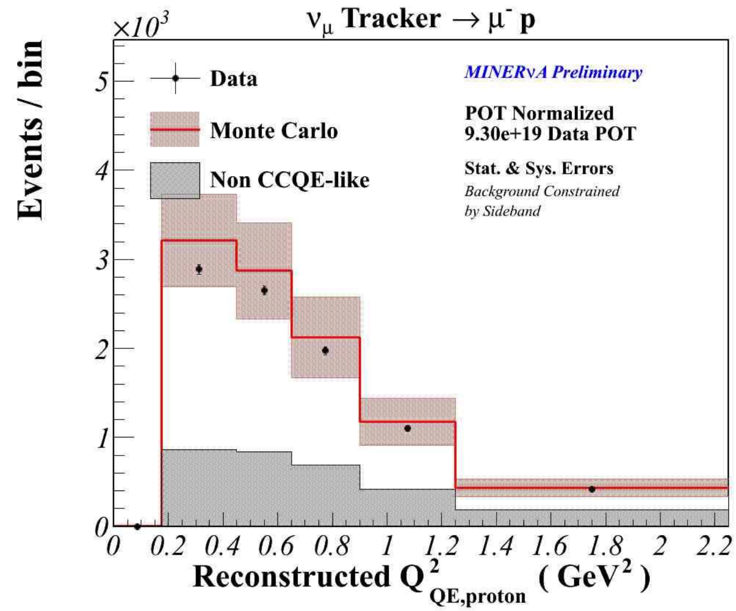
Next steps:

1. Ratio of the cross-section.
2. Quantify the final state interactions.

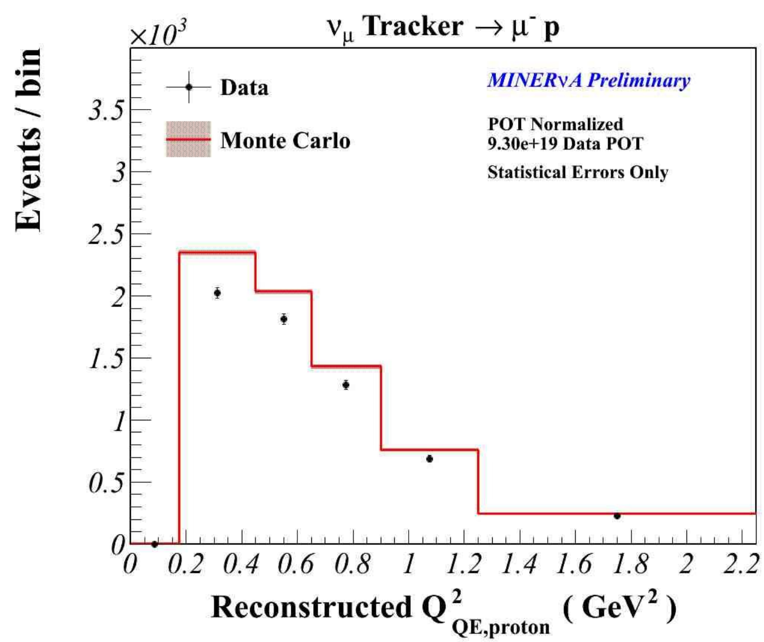
Reconstructing Kinematics from the Proton



Constrain the background



Subtract the background

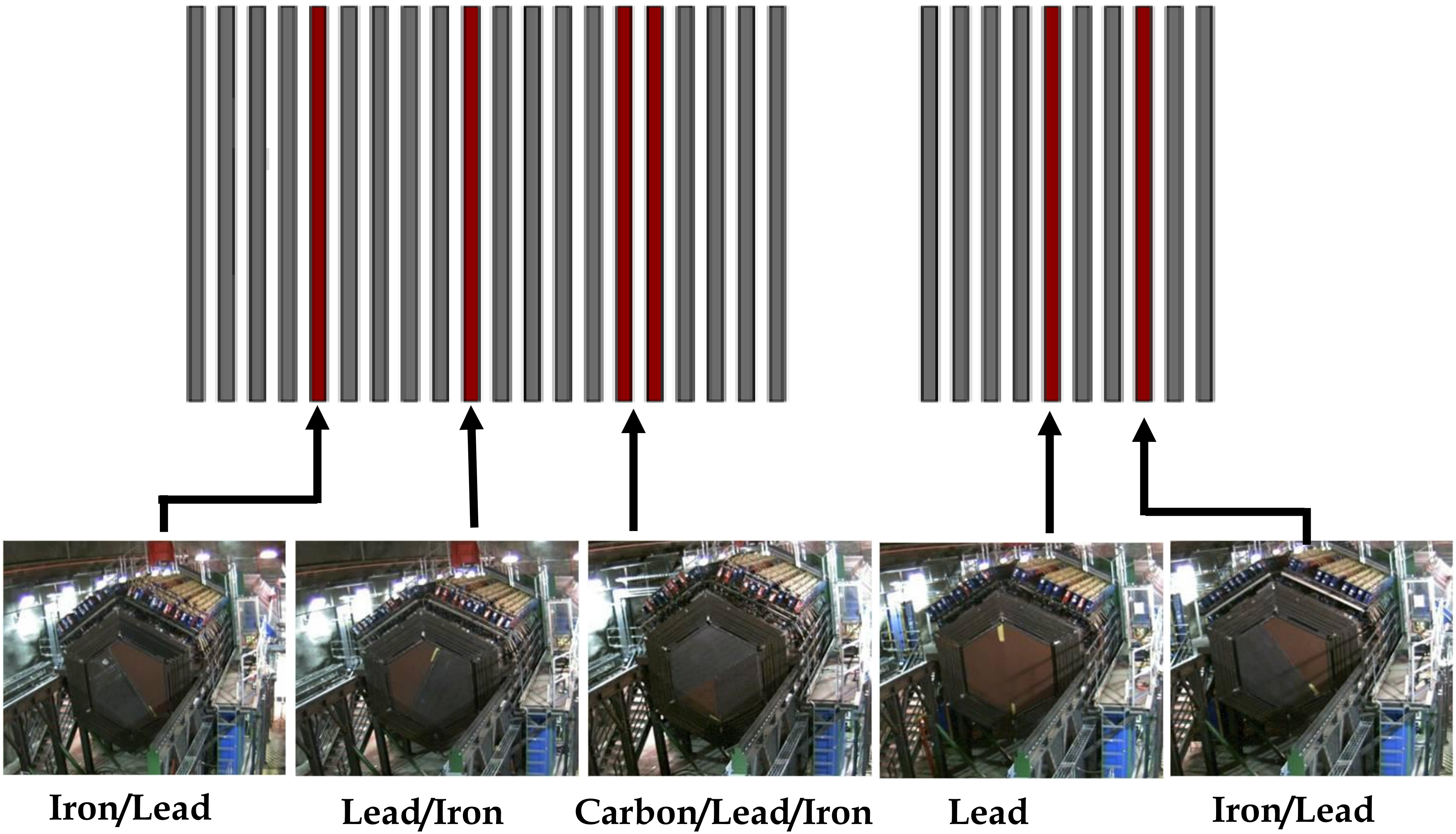


<u>Next steps:</u>

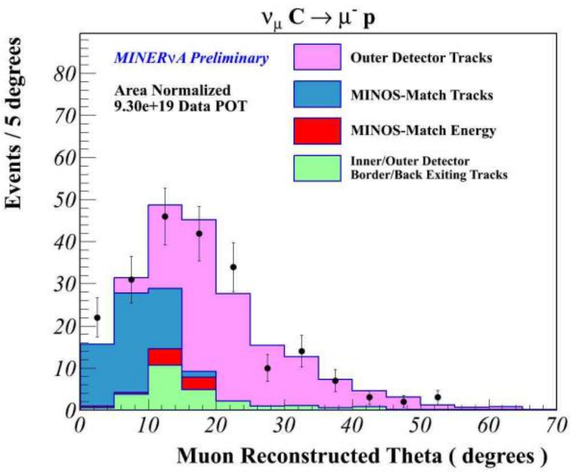
1. Cross sections.
2. Use this sample to normalize the C, Fe, and Pb cross section measurement s.

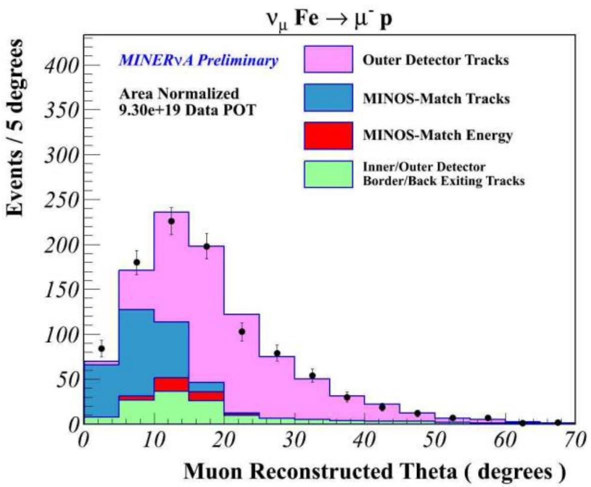
2-track ν_μ CCQE in the Nuclear Targets Region

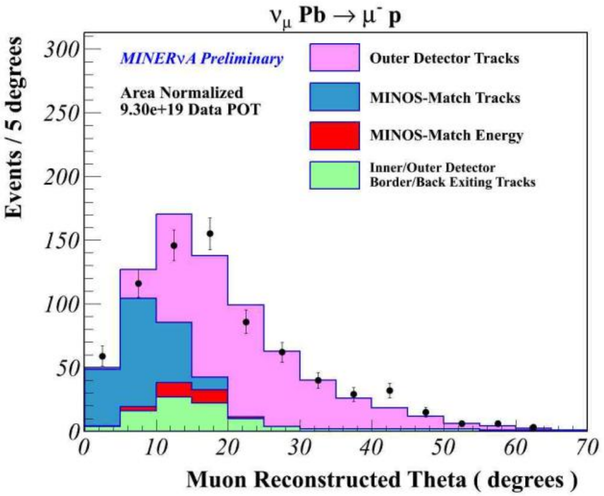
2-track ν_μ CC QE in the Nuclear Targets



2-track ν_μ CC QE in the Nuclear Targets

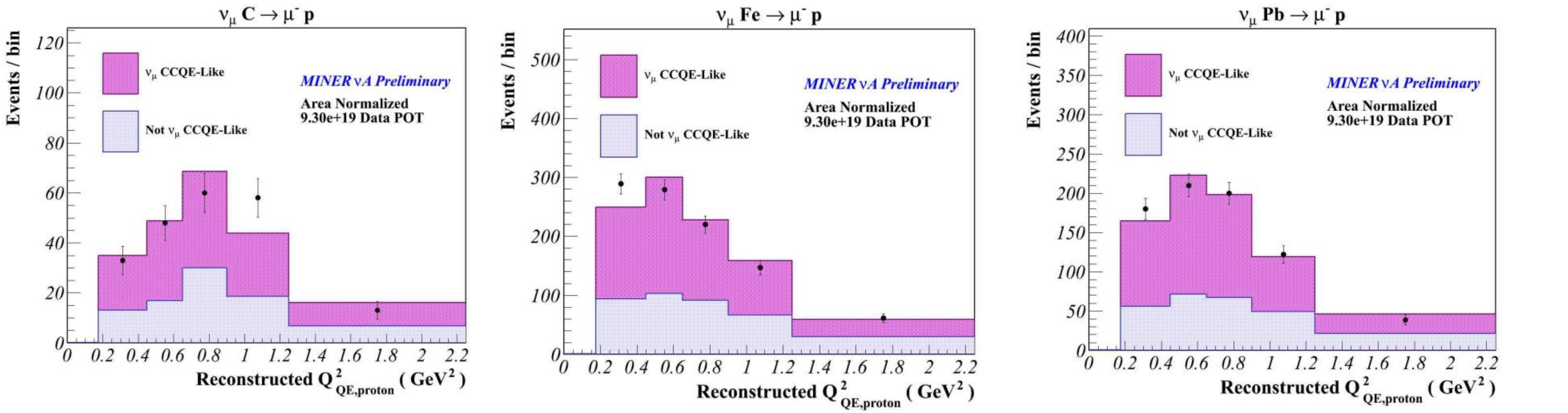






- Majority of the muons are matched to energy in the Outer Detector.
- The poor acceptance for MINOS matched tracks is due to the following:
    - Location of the nuclear targets in the detector.
    - Requiring the proton to be tracked.

2-track ν_μ CC QE in the Nuclear Targets



Next steps:

- Include the full data set
- Background Subtraction
- Cross-sections (Ratios)