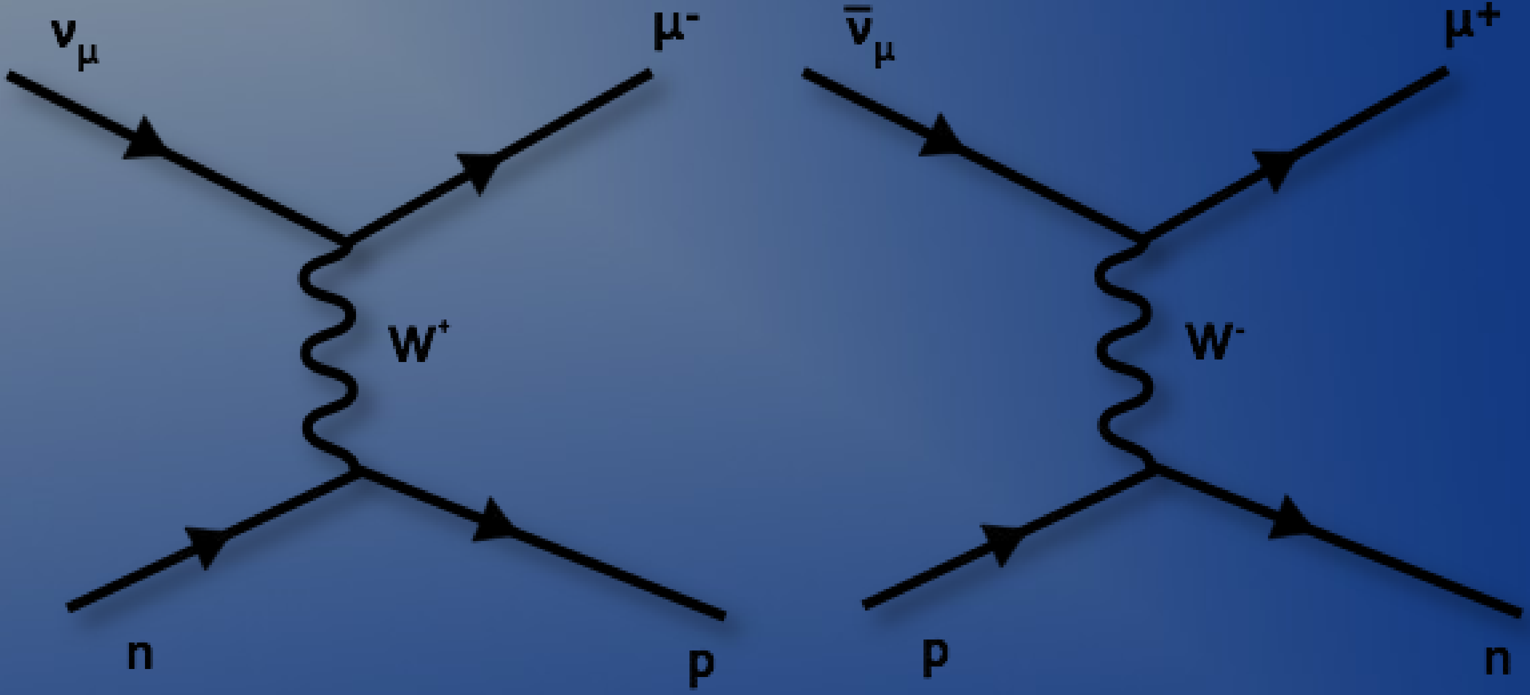
Charged Current Quasi-Elastic Scattering in MINERvA

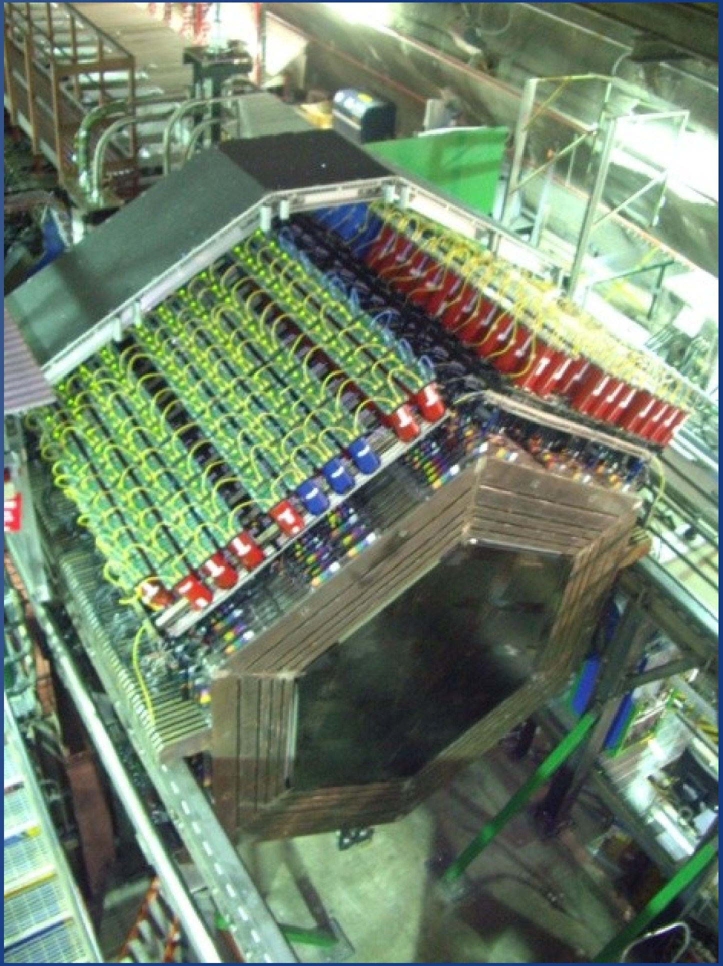


Jesse Chvojka – University of Rochester

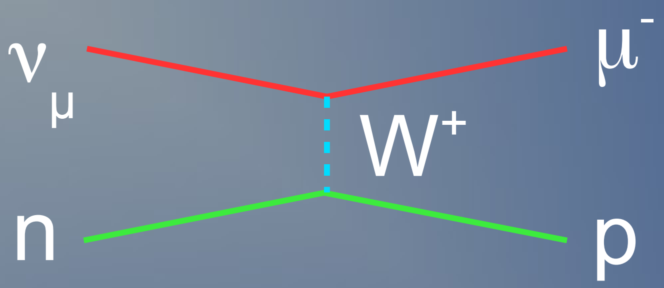
NuFact – July 24th, 2012

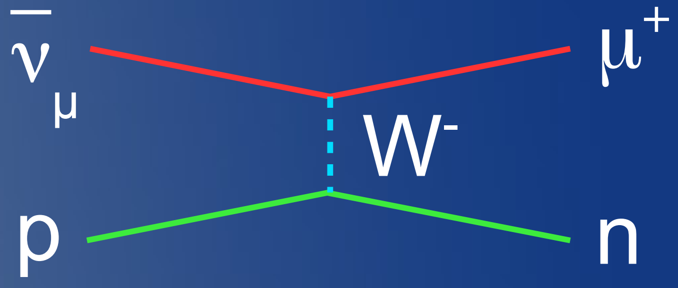
Overview

- Description of Charged Current Quasi-Elastic (CCQE) Scattering
- Physics Motivation
- NuMI Beamline and MINERvA
- Single track anti-neutrino CCQE
- Single track neutrino CCQE
- Two track neutrino CCQE events on scintillator and on nuclear targets
- Conclusions



What is CCQE Scattering?





$$\nu_\mu + n \rightarrow \mu^- + p \qquad \bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

- For neutrino CCQE scattering, proton will be tracked if momentum is above threshold
  - Have one and two track analyses dependent on proton reconstruction
- For anti-neutrino CCQE scattering the neutron will not necessarily be observed

Reconstruction Assuming Elastic Kinematics

- Incoming neutrino or anti-neutrino energy and momentum transfer squared (Q^2) can be reconstructed with just the muon kinematics

$$E_{\nu_\mu}^{QE} = \frac{2M_n' E_\mu - \left(M_n'^2 + m_\mu^2 - m_p^2\right)}{2\left(M_n'^2 - E_\mu + p_\mu \cos\theta_\mu\right)}$$

$$E_{\bar{\nu}_\mu}^{QE} = \frac{2M_p' E_\mu - \left(M_p'^2 + m_\mu^2 - m_n^2\right)}{2\left(M_p'^2 - E_\mu + p_\mu \cos\theta_\mu\right)}$$

$$Q^2 = 2E^{QE}\left(E_\mu - p_\mu \cos\theta_\mu\right) - m_\mu^2$$

$$M_n' = m_n - \varepsilon_B$$

$$M_p' = m_p - \varepsilon_B$$

$$\varepsilon_B = 30\ MeV$$

$$E^{QE} = E_{\bar{\nu}_\mu}^{QE} \text{ or } E_{\nu_\mu}^{QE}$$

Uses Relativistic Fermi Gas Model (RFGM)

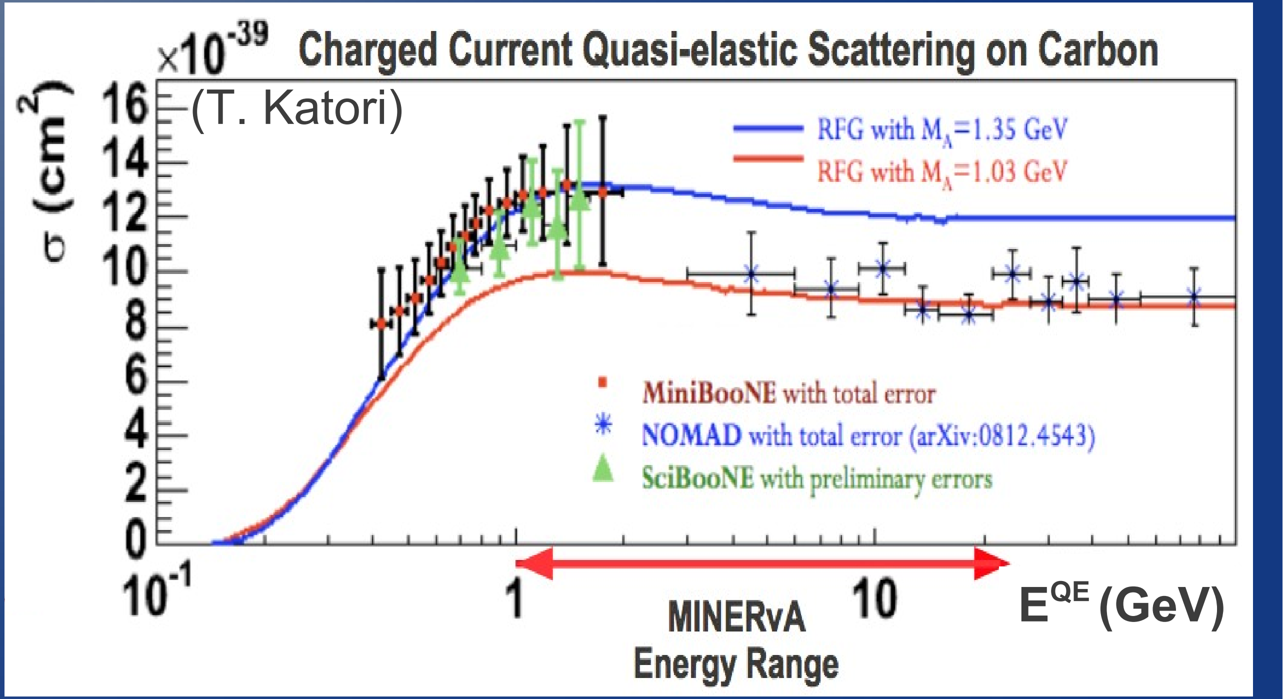
CCQE Cross-Section

- Cross section calculated using a variety of form factors
  - Vector form factors extracted from electron-proton scattering
  - Axial vector form factor (Dipole Approximation shown below) can be most easily extracted from neutrino-nucleus scattering

$$F_A(Q^2) = \frac{-g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2} \qquad M_A = Axial\,Vector\,Mass$$

Motivation

- Cross-sections are a big systematic error for oscillation experiments
- Contradictory measurements
- Experiments looking for CP violation by measuring differences in oscillations between neutrinos and anti-neutrinos will be systematics dominated due to the size of θ_{13}



(T. Katori)

The NuMI Beam Line

- Neutrinos/anti-neutrinos created from decaying pions and kaons created from proton interactions with target
- Ability to predict pion and kaon production off the target is the largest uncertainty in determining our flux

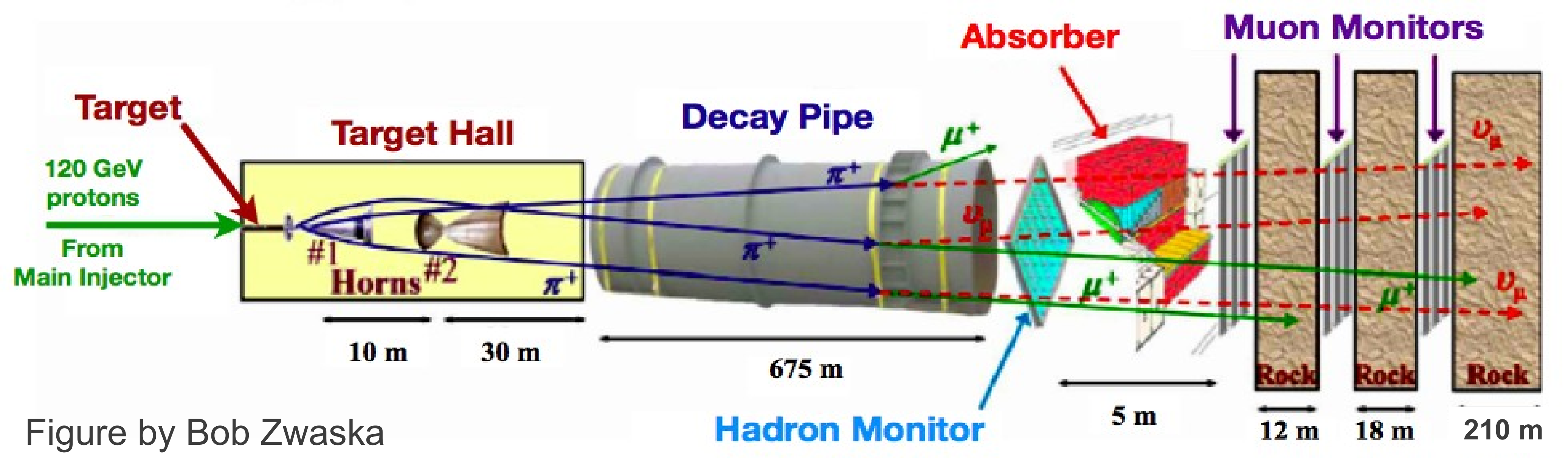


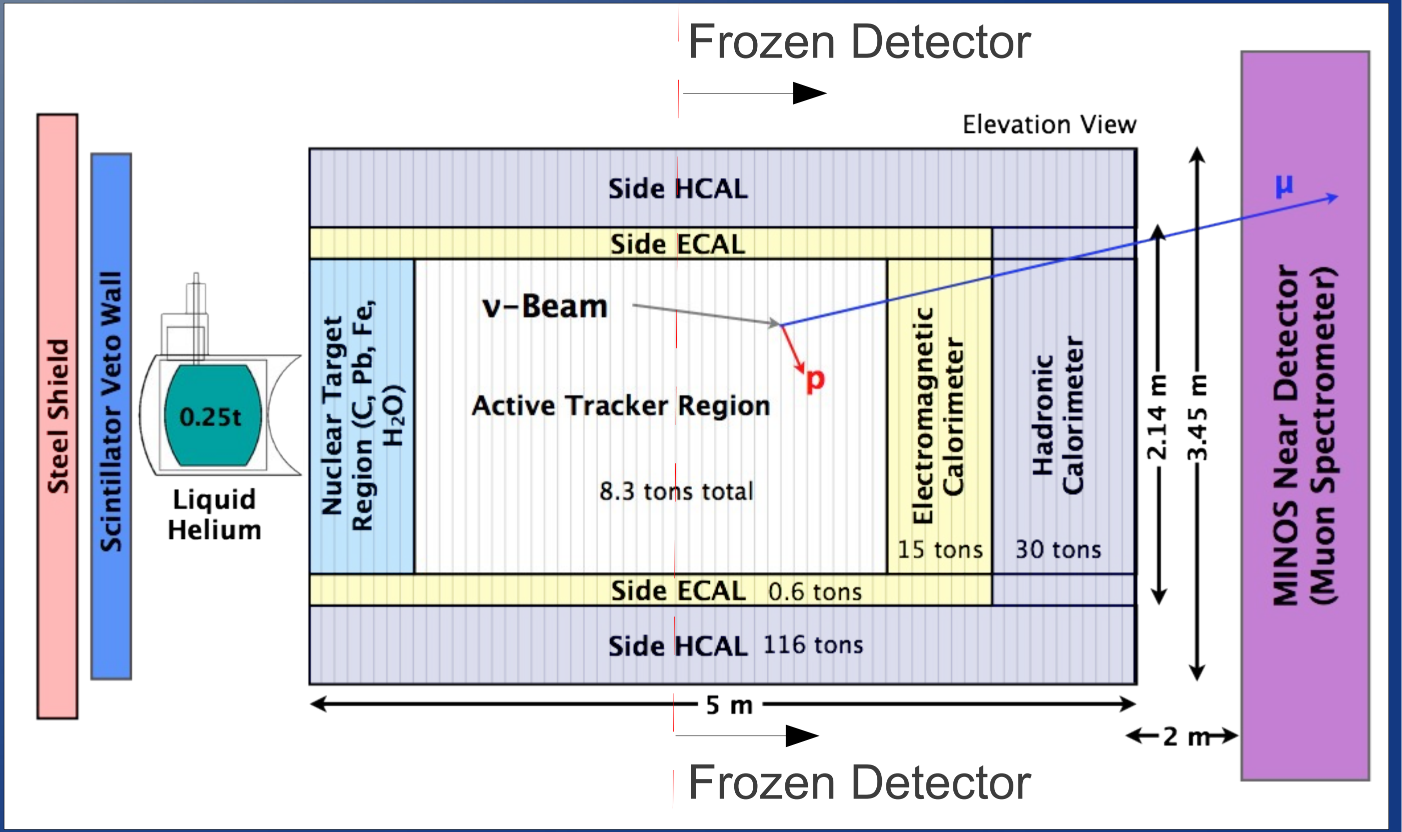
Figure by Bob Zwaska

The MINERvA Detector

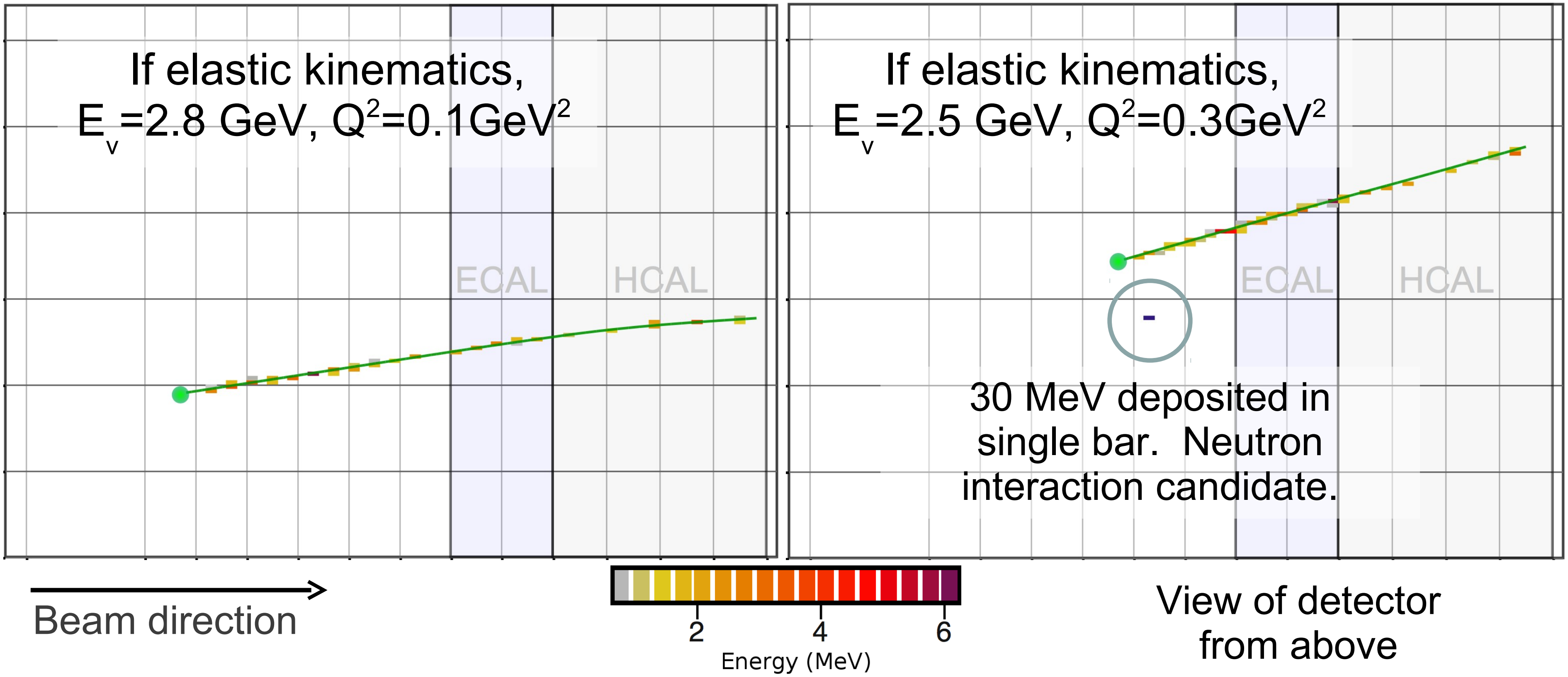
- Fine grained detector that lies upstream of the MINOS Near Detector (our muon spectrometer)
- Anti-neutrino data taken with a partially constructed detector

We show:

- ~9e19 POT worth of anti-neutrino data (16% of total)
- ~9.5e19 POT worth of neutrino data (25% of total)



$\bar{\nu}_\mu$ CCQE Single Track Analysis


If elastic kinematics,
E_ν=2.8 GeV, Q^2=0.1GeV^2

If elastic kinematics,
E_ν=2.5 GeV, Q^2=0.3GeV^2

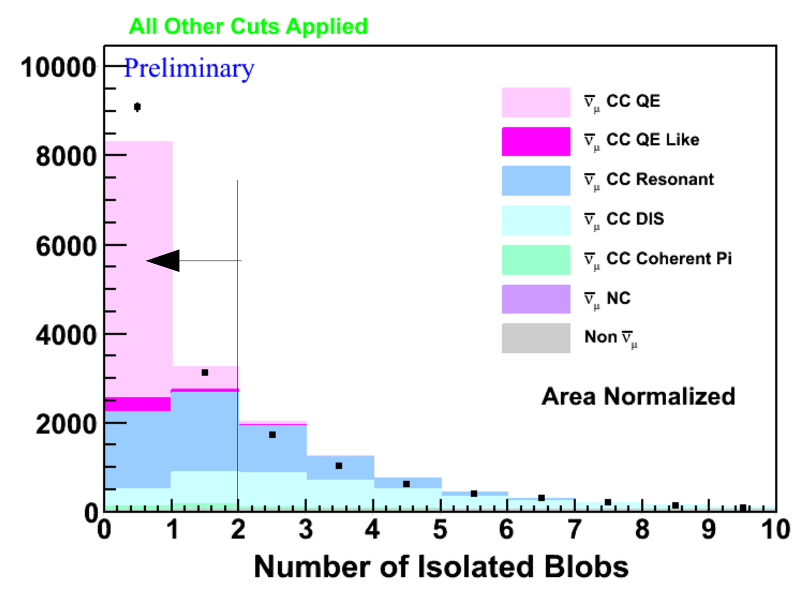
30 MeV deposited in single bar. Neutron interaction candidate.

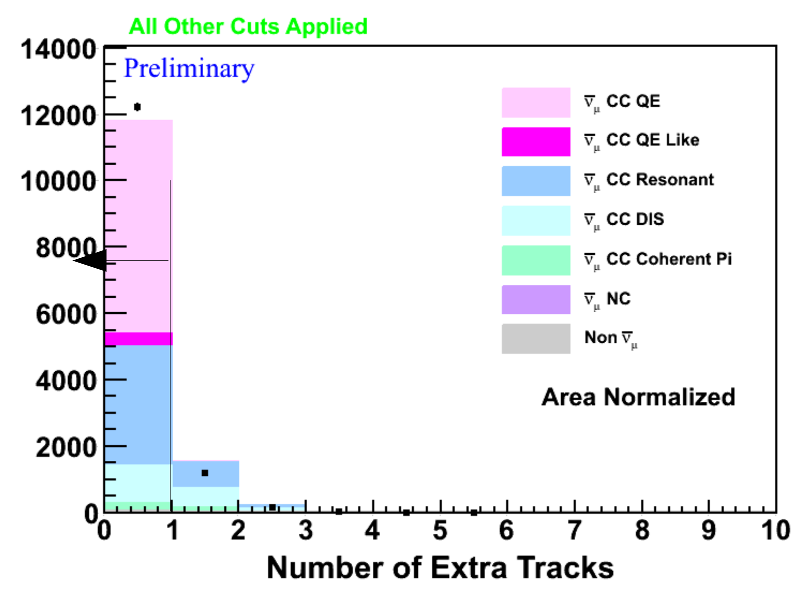
Beam direction

View of detector from above

Selecting a $\bar{\nu}_\mu$ CCQE Sample

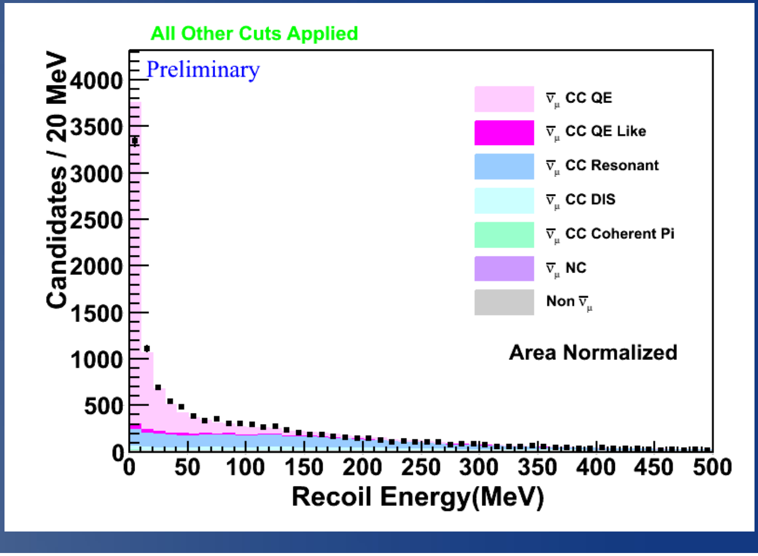
- Require event in the tracker region of MINERvA (scintillator (CH)) that matches to a μ^+ in MINOS
- Low activity and limited dead time upstream of muon
- ≤ 1 localized area of recoil energy deposit (blob)
- No extra tracks
- Cut on overall recoil energy

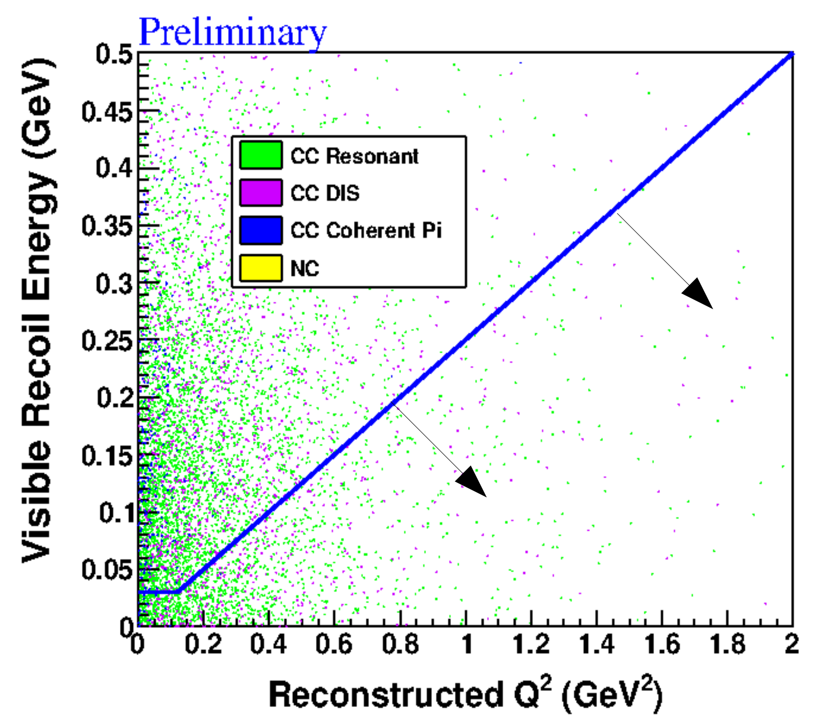


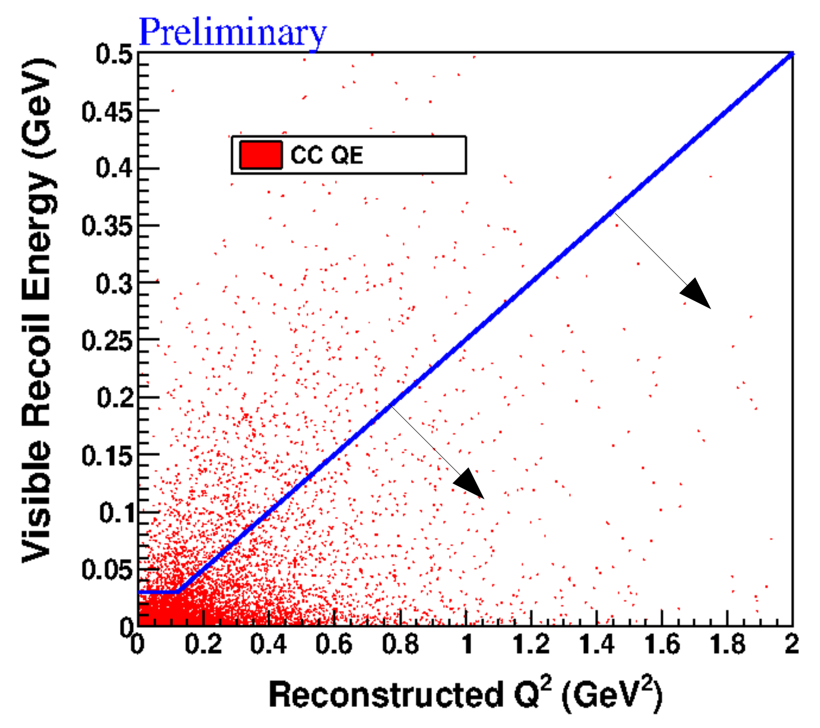


Selecting a CCQE Sample

- Expect higher Q^2_{QE} events to have more recoil energy
- Scale recoil cut with Q^2_{QE}

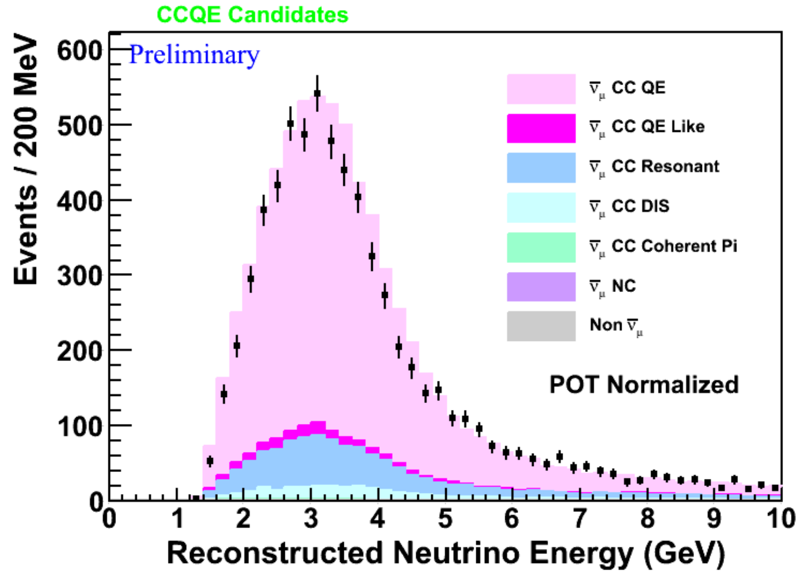


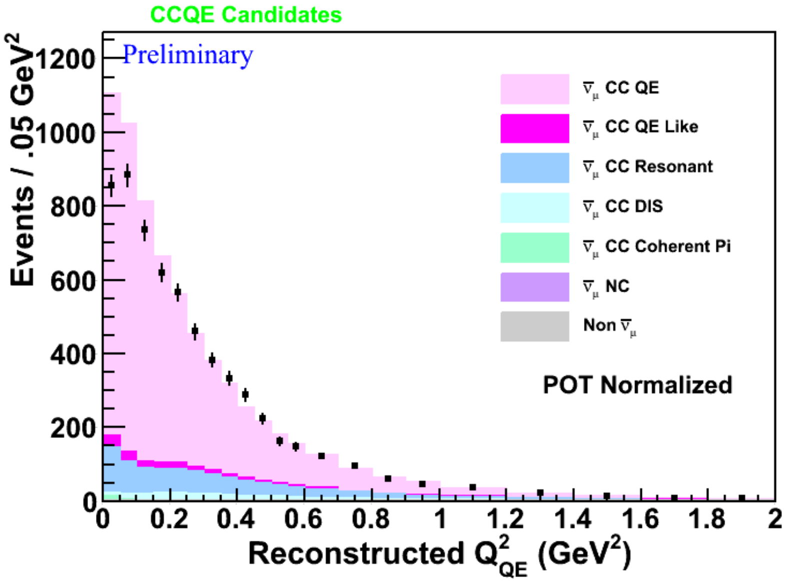


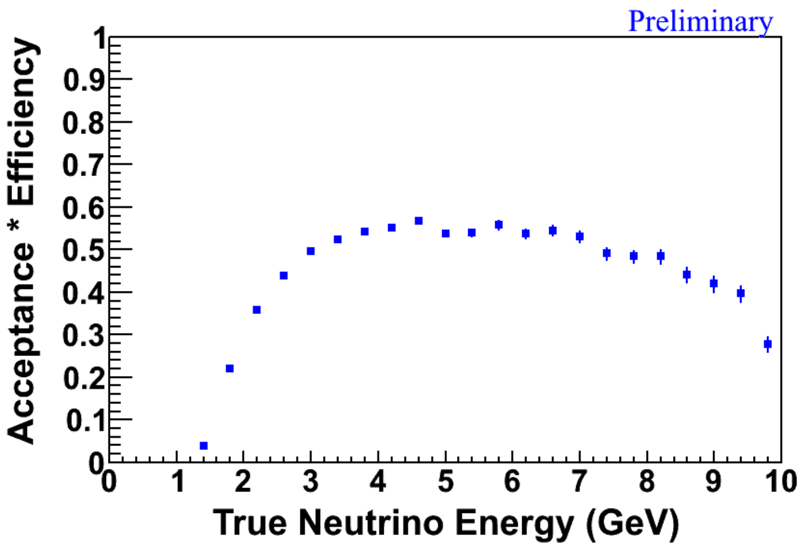


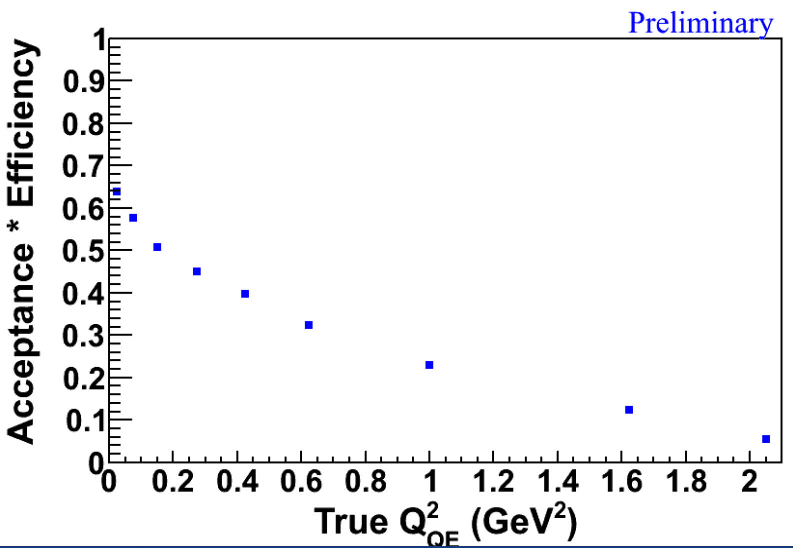
Neutrino Energy and Q^2_{QE}

- After all cuts are applied, sample has ~80% purity

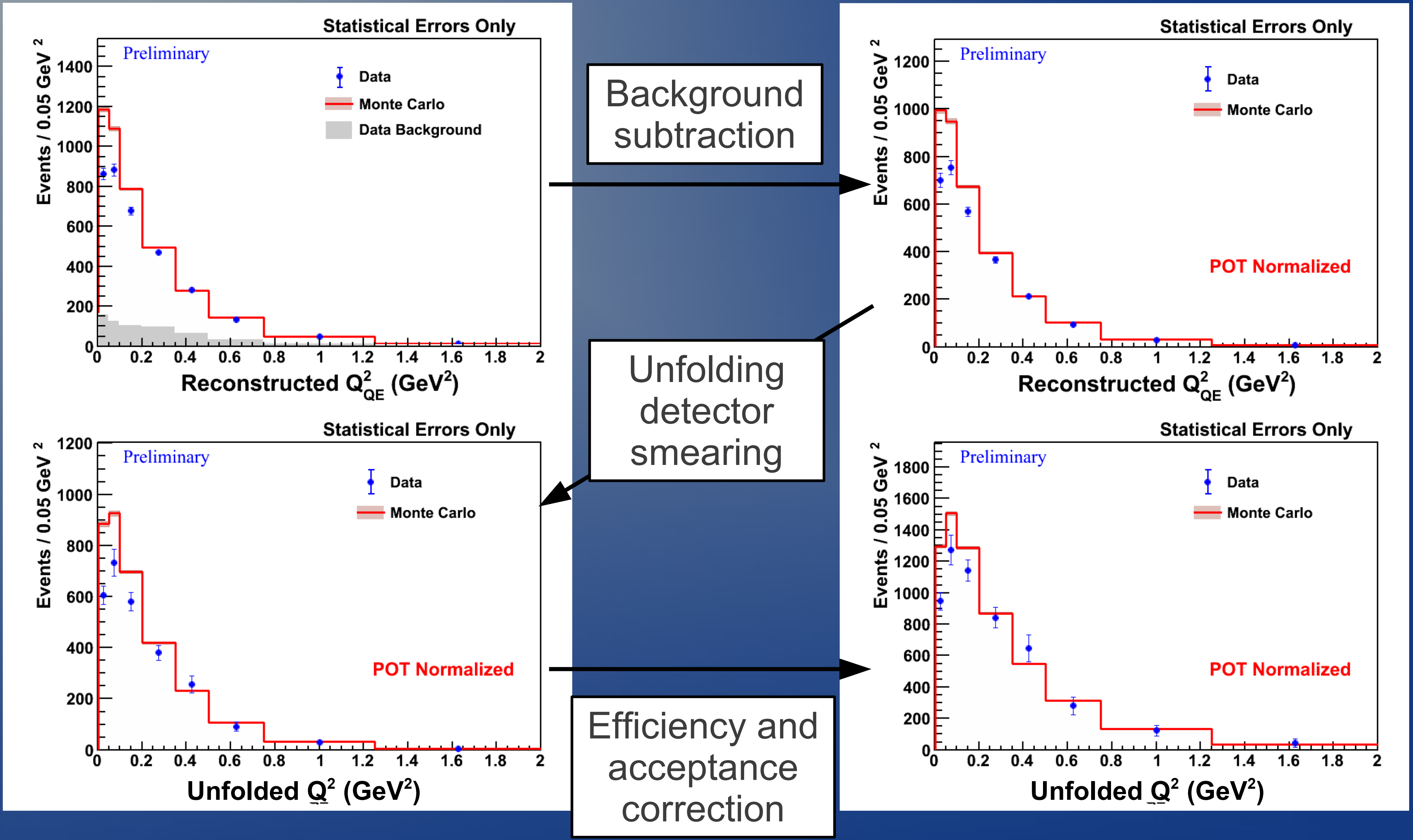








Finding $d\sigma/dQ^2_{QE}$



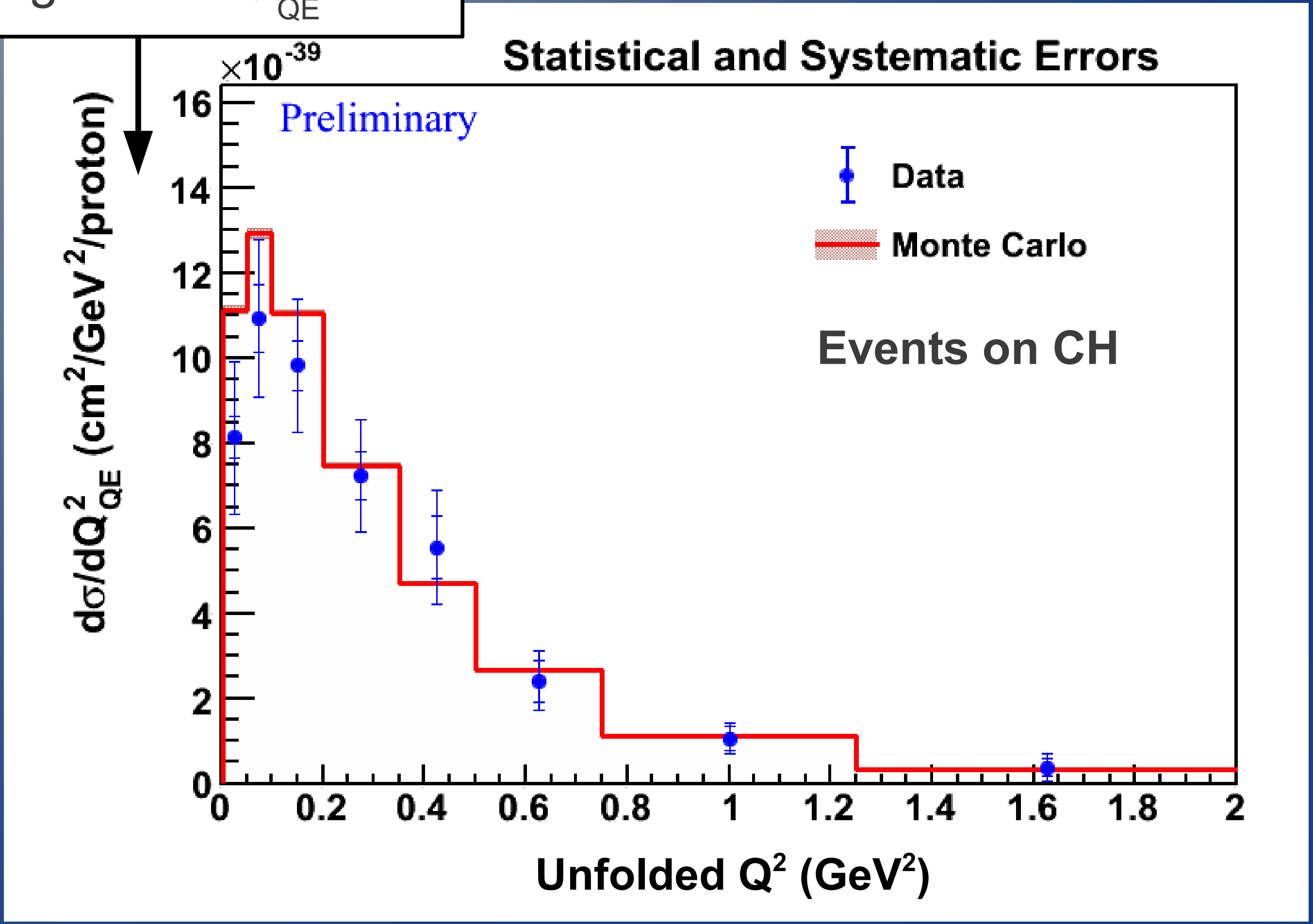
Background subtraction

Unfolding detector smearing

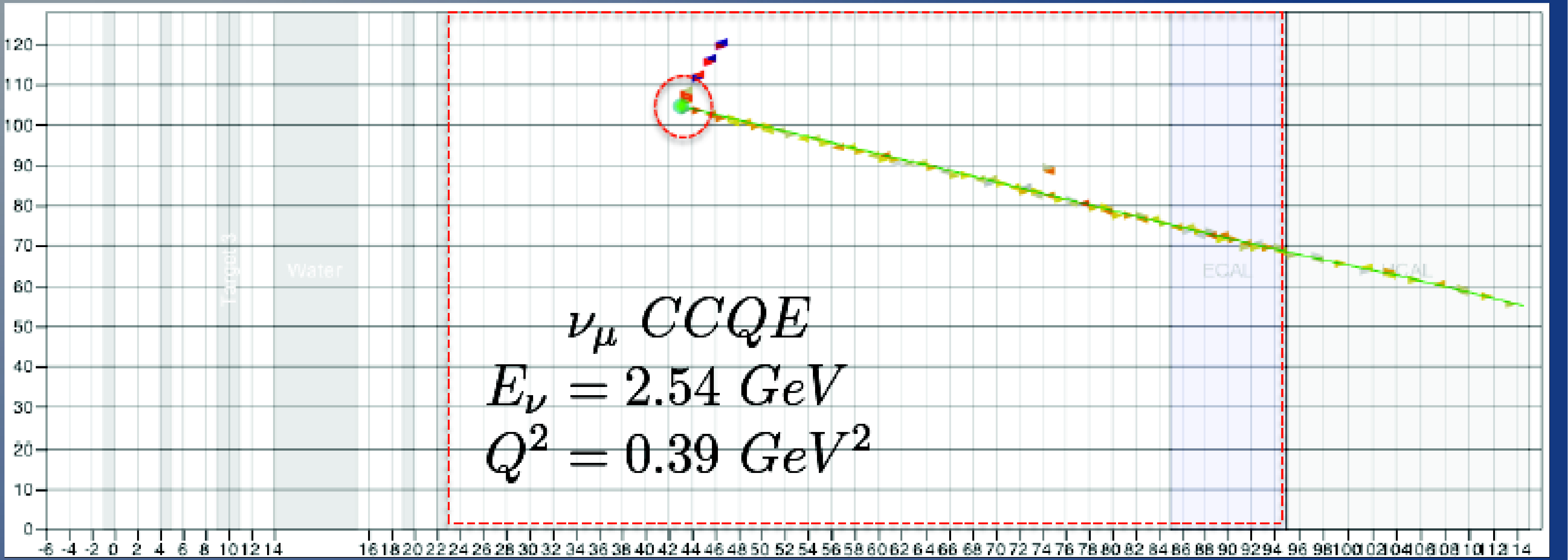
Efficiency and acceptance correction

Finding $d\sigma/dQ^2_{QE}$

Divide by flux and number of target protons to get $d\sigma/dQ^2_{QE}$



ν_μ CCQE Single Track Analysis

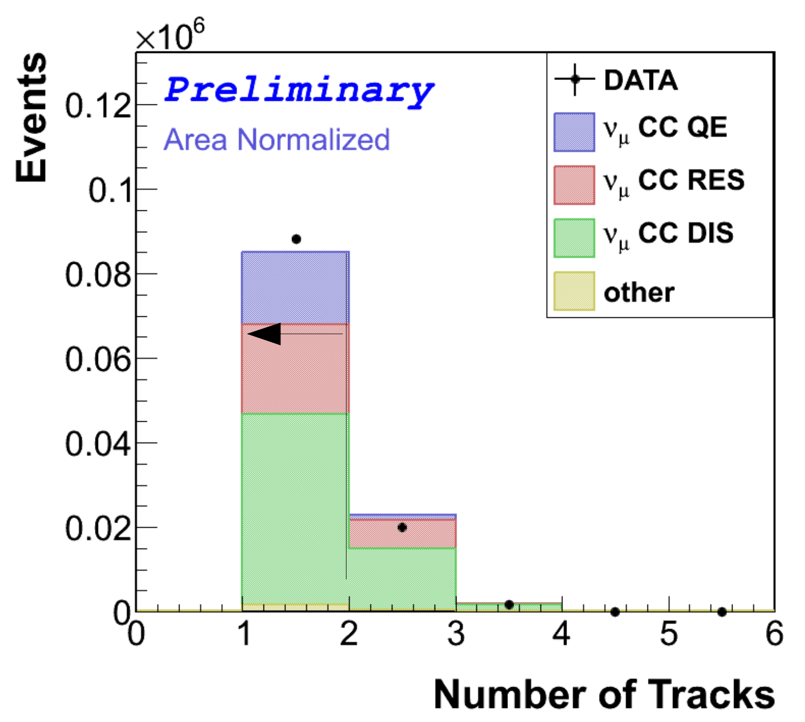


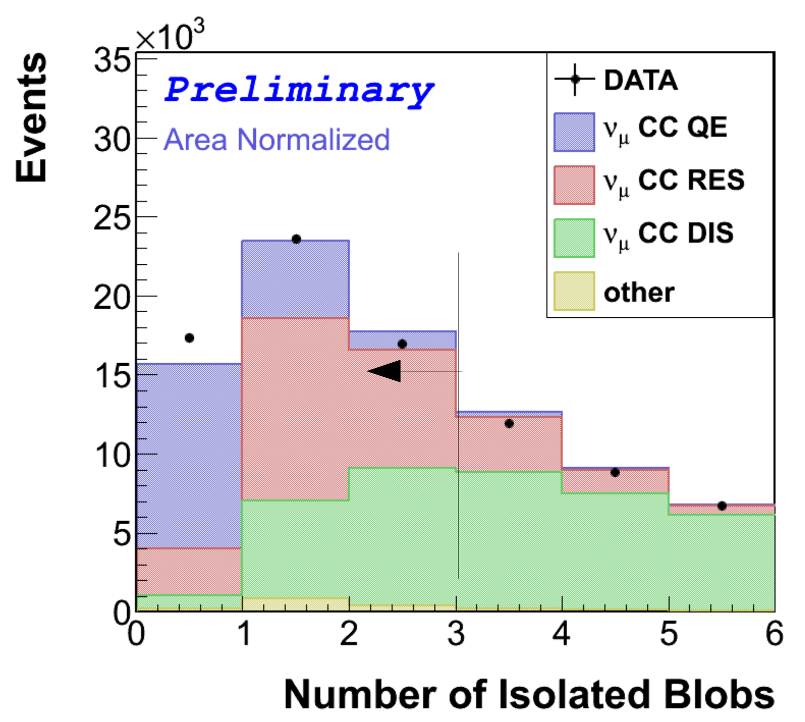
$$\nu_\mu\ CCQE$$
$$E_\nu = 2.54\ GeV$$
$$Q^2 = 0.39\ GeV^2$$

- Select single track events in the scintillator region matched to μ^- reconstructed in MINOS
- Require no dead time upstream of the muon track

Signal Selection

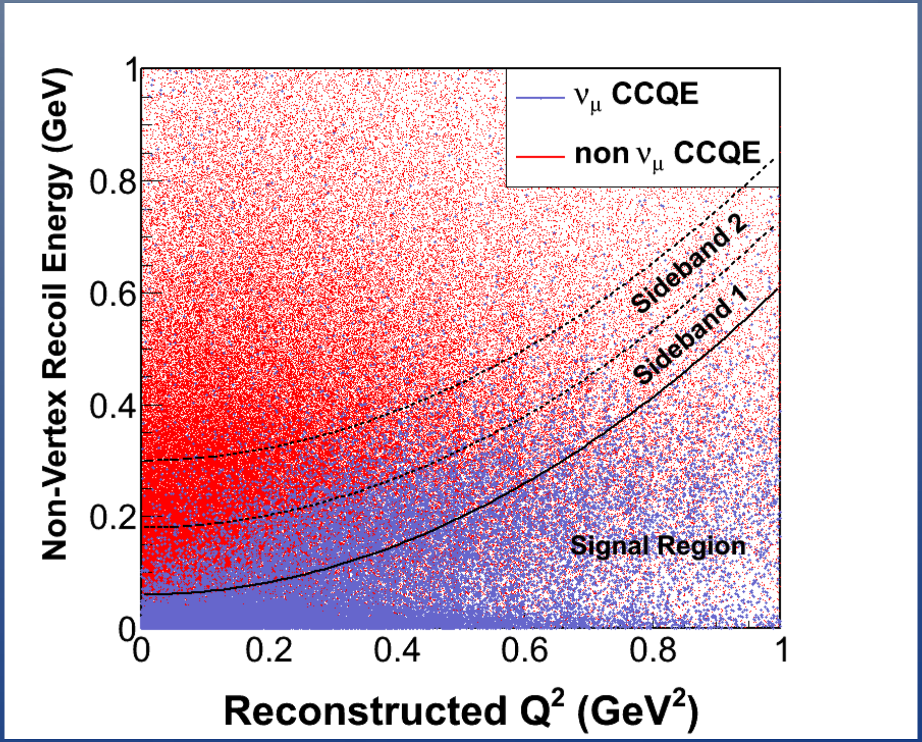
- Require no additional tracks
- Require no more than two showery type deposits (isolated blobs)

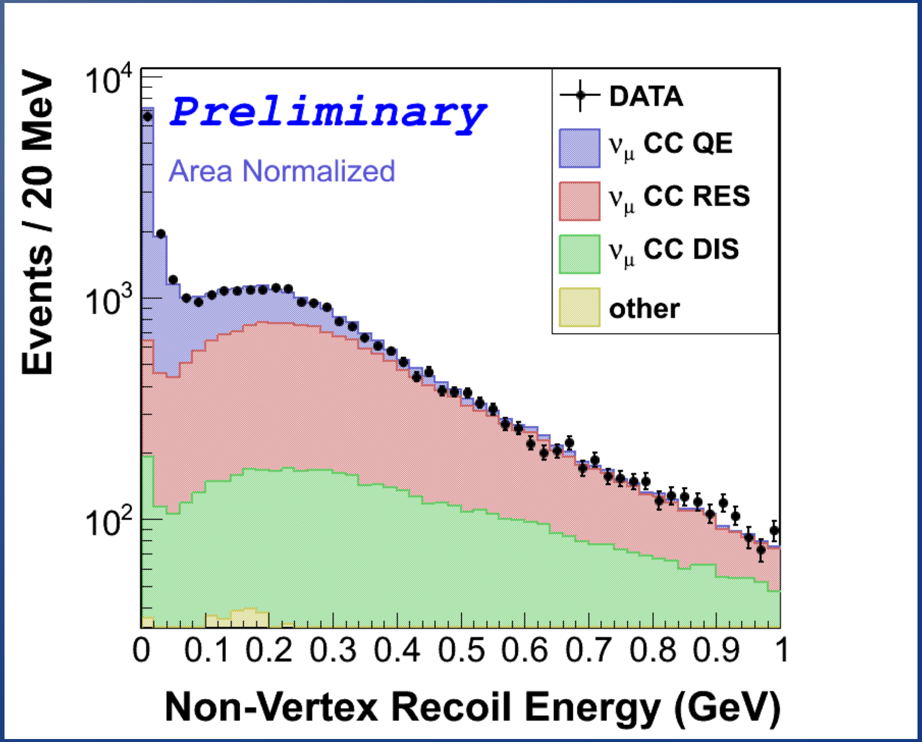




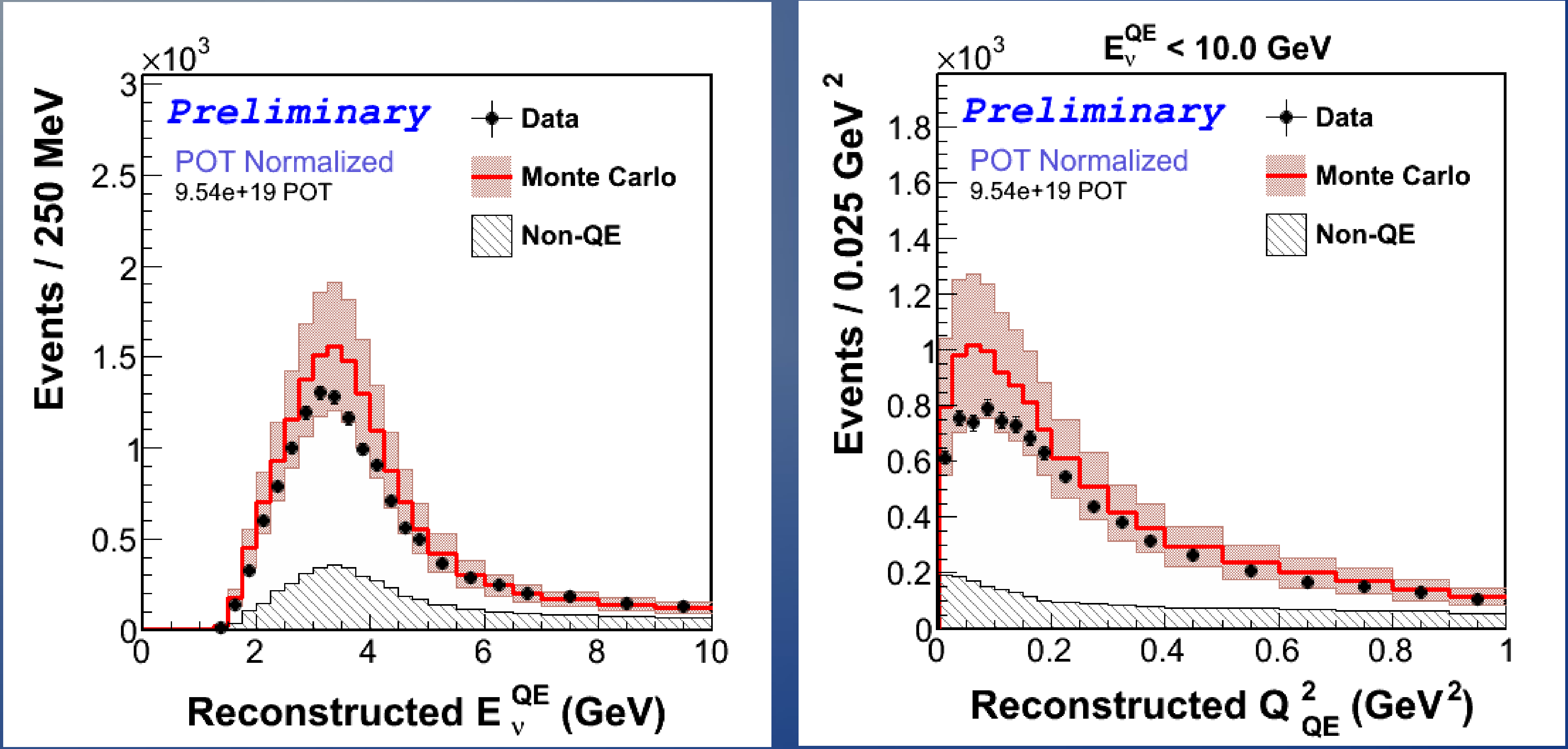
Signal Selection

- Selection on recoil energy scales with Q^2 and excludes energy near the vertex
  - Energy near vertex is affected by Final State Interactions, which are poorly modeled

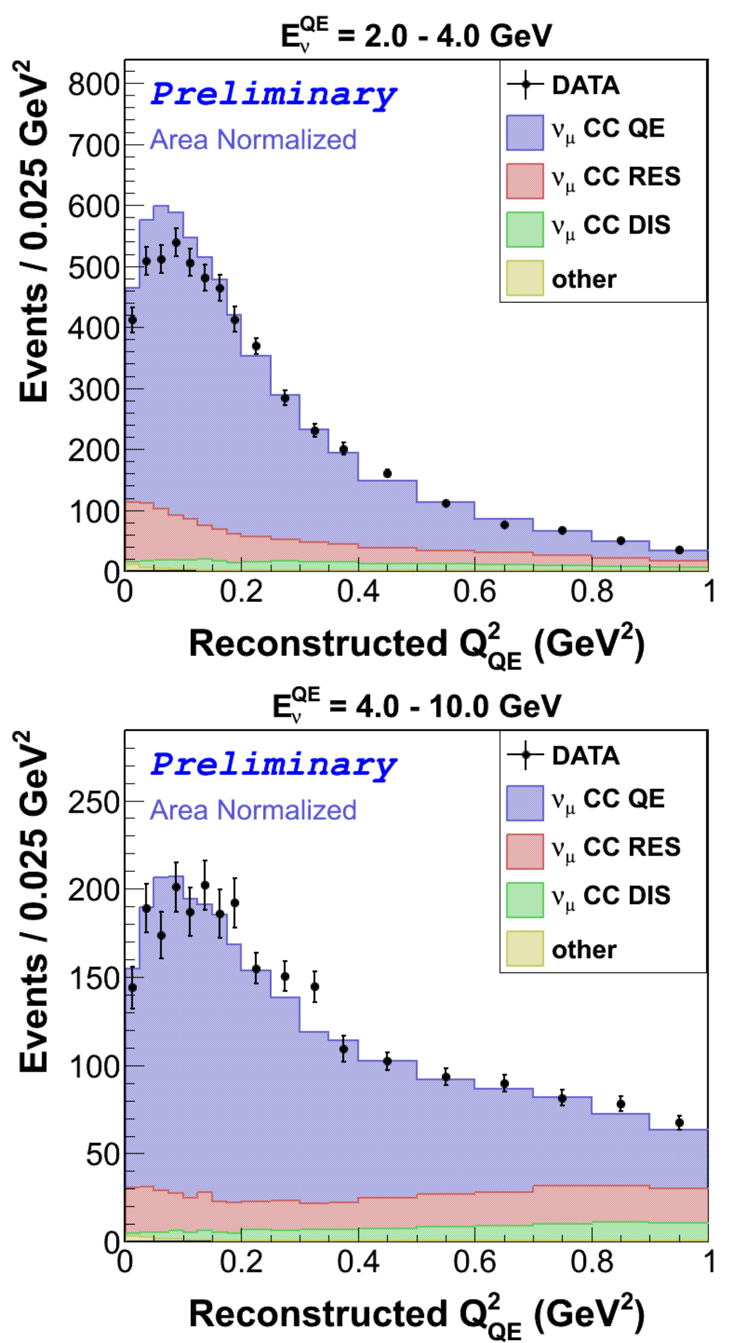


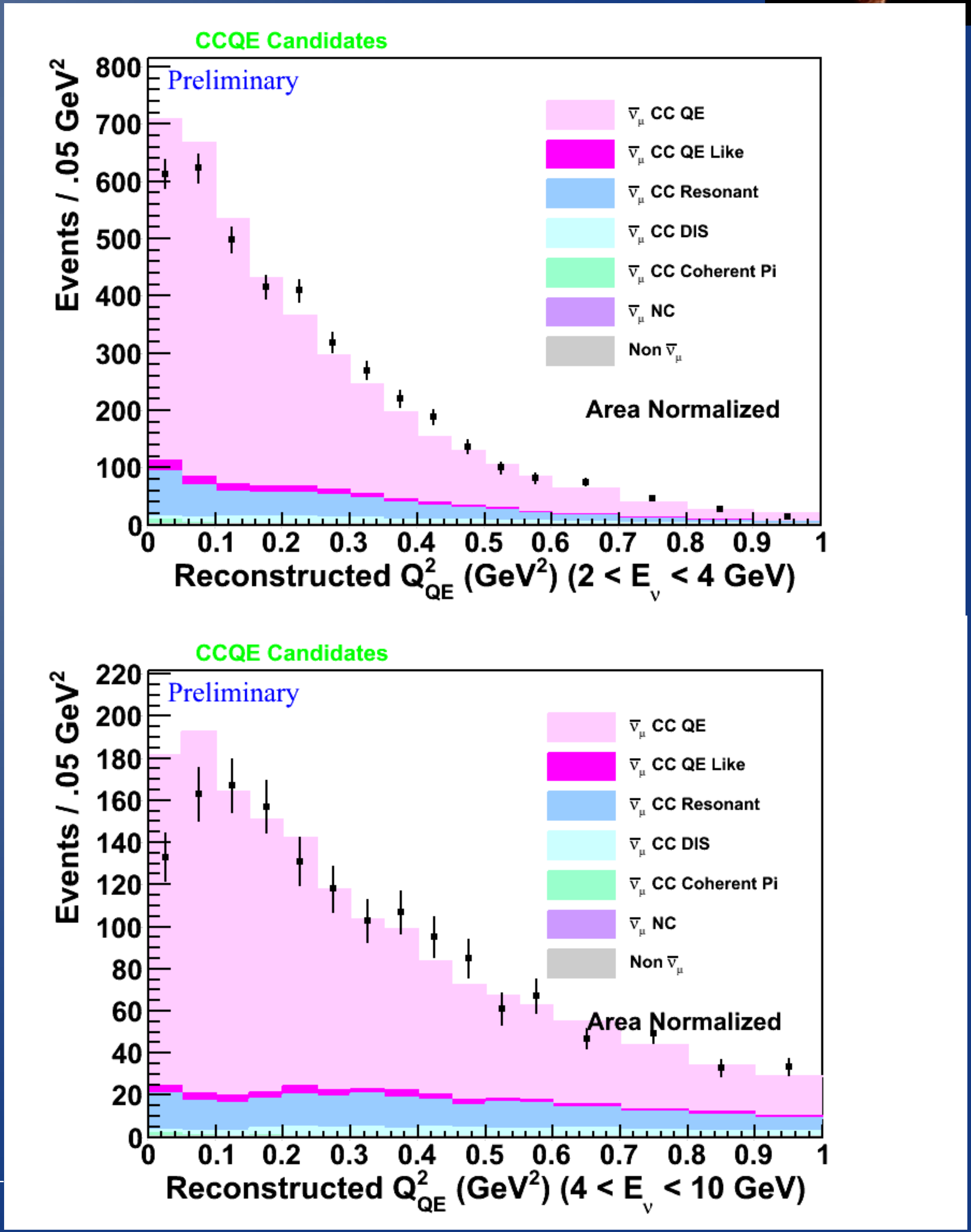


Reconstructed Energy and Q^2

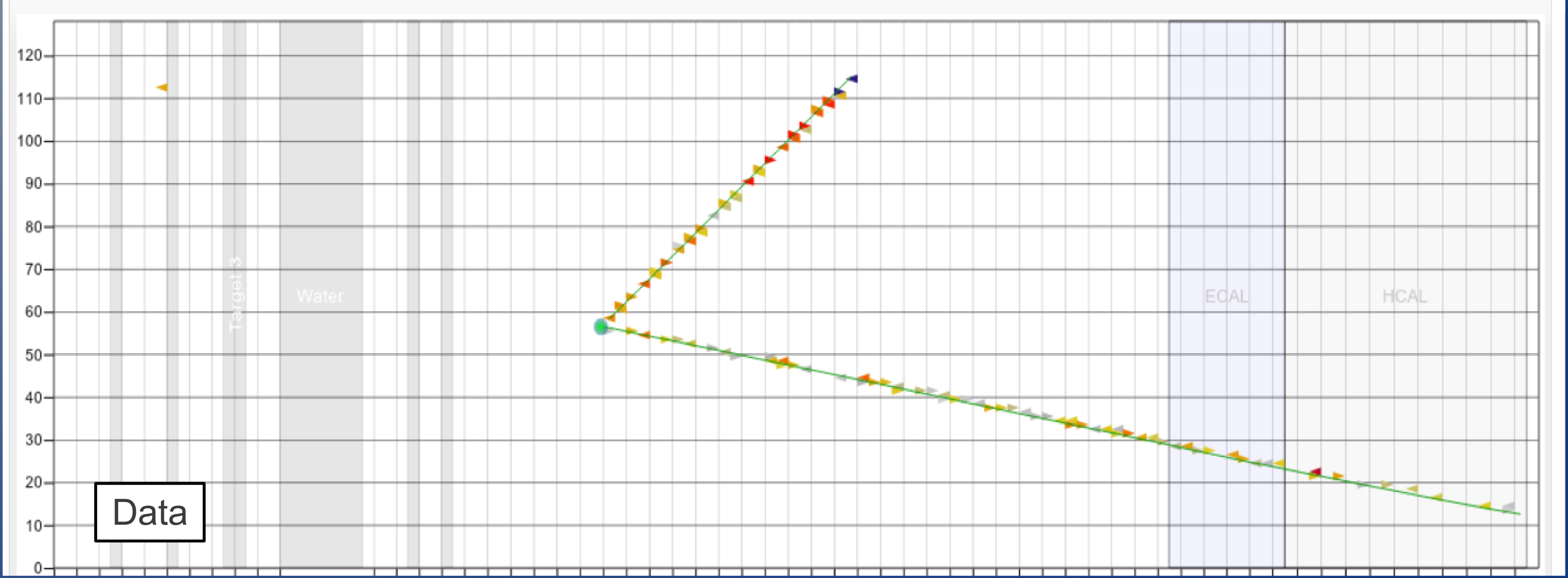


Comparing Single Track ν_μ and $\bar{\nu}_\mu$



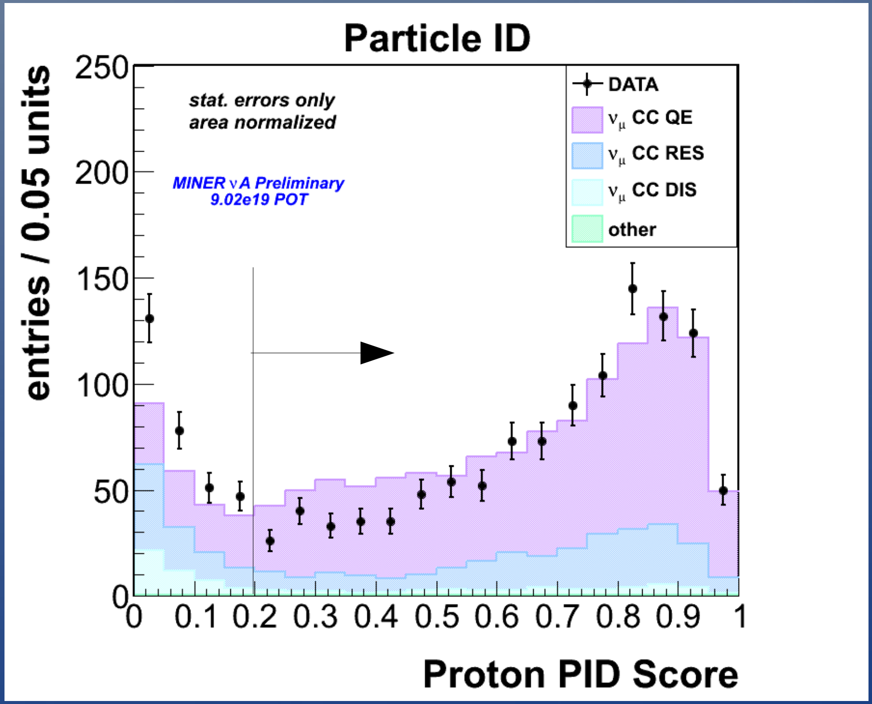


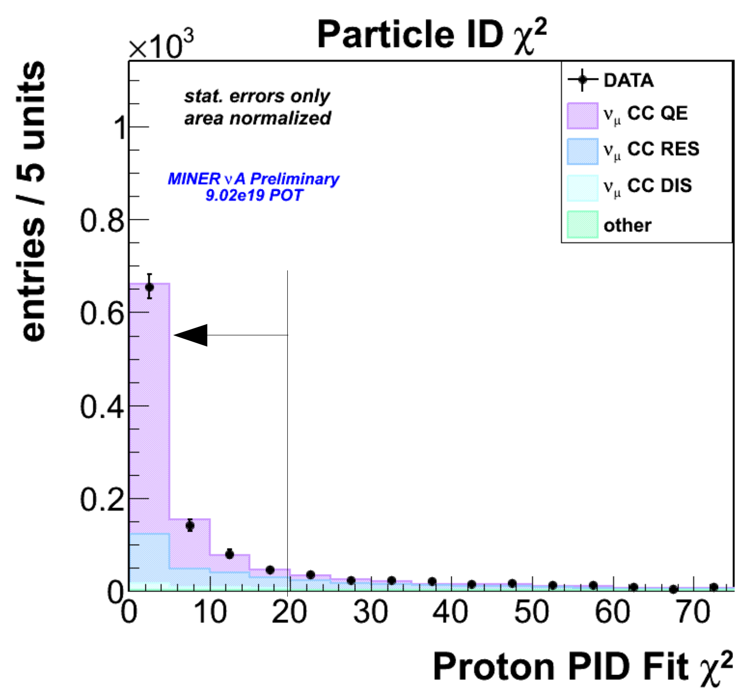
ν_μ CCQE Two Track Events in Scintillator



Selecting Two Tracks Events in Scintillator

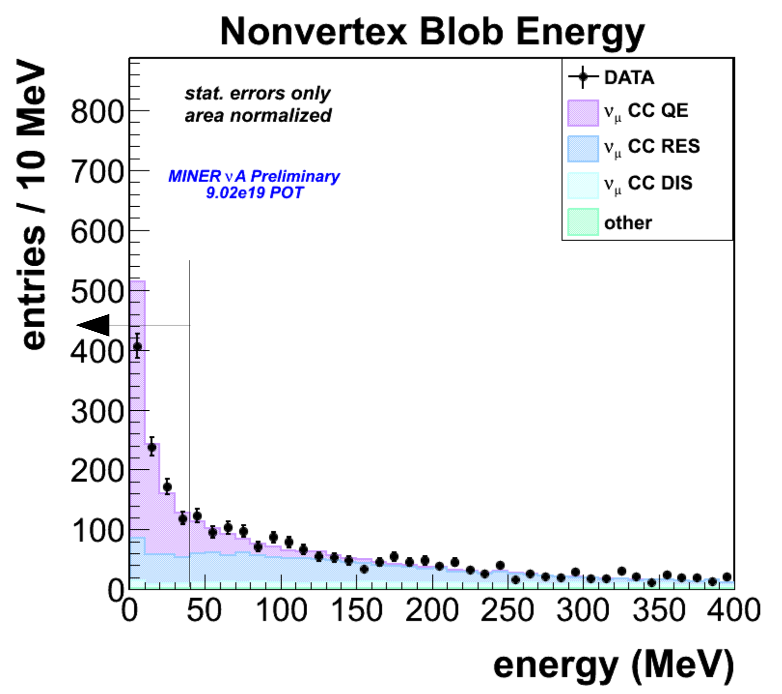
- Require two tracks with common vertex
- Require muon matched to MINOS, contained proton
- Make cut on proton reconstruction

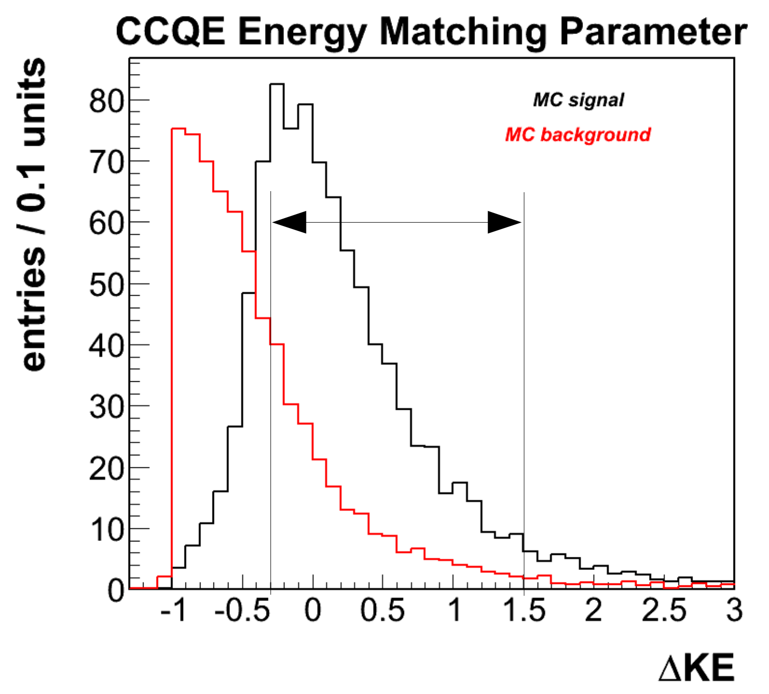




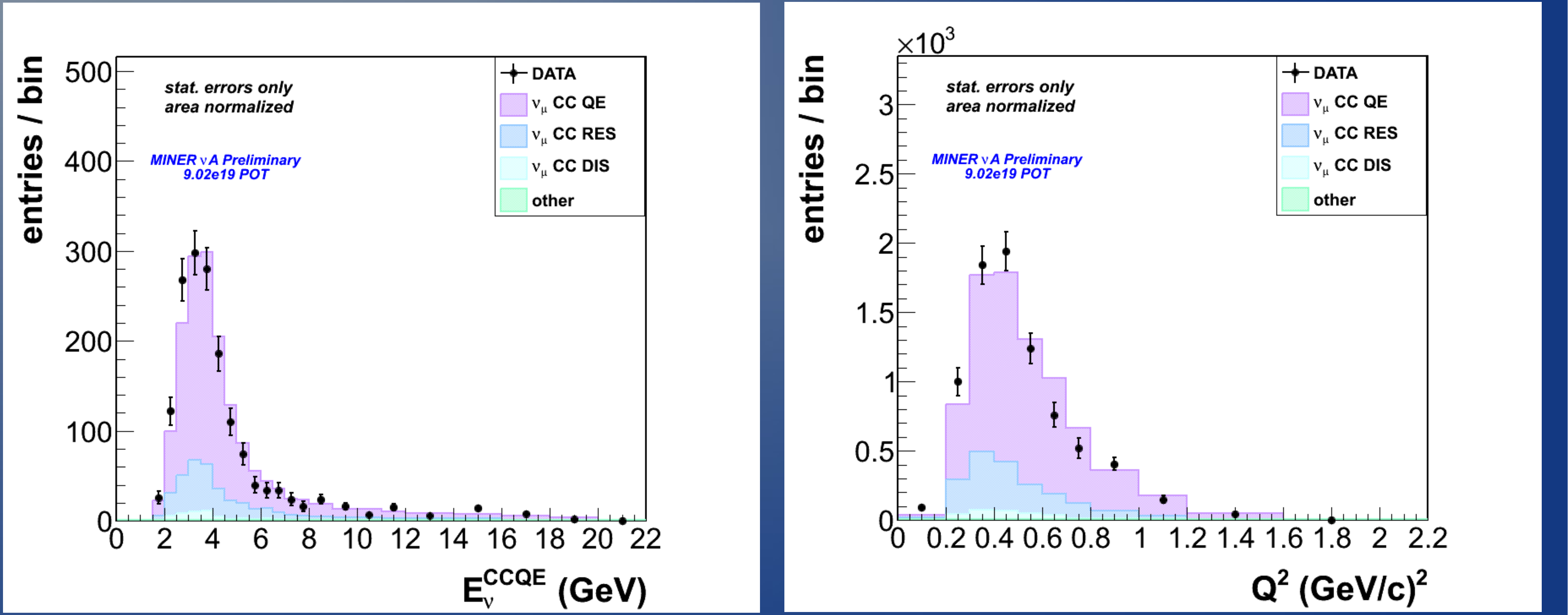
Selecting Two Tracks Events in Scintillator

- Expect little energy off of muon or proton track → 40 MeV cut on energy deposit in the detector
- Restrict expected proton kinetic energy using both proton and muon information



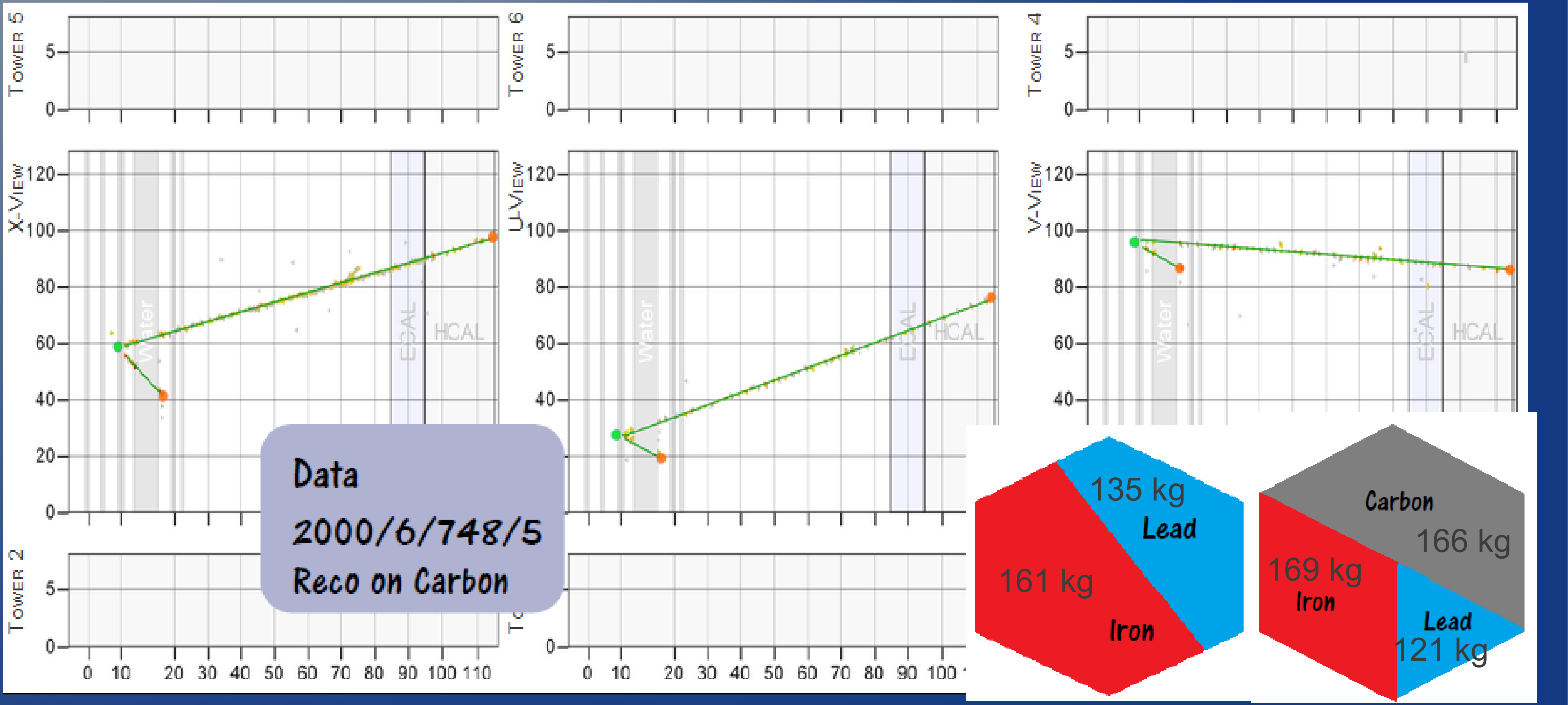


Neutrino Energy and Q^2 for the Two Track Sample



Update on ν_μ CCQE Two Track Events on Nuclear Targets

- Analysis looked at two track CCQE events on graphite, iron, and lead targets (depicted below)



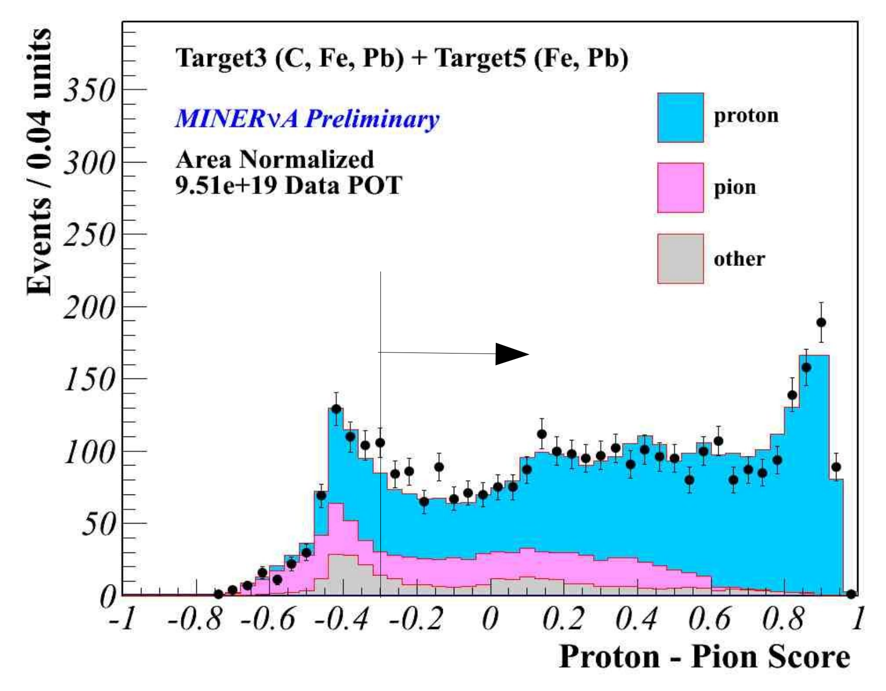
Data

2000/6/748/5

Reco on Carbon

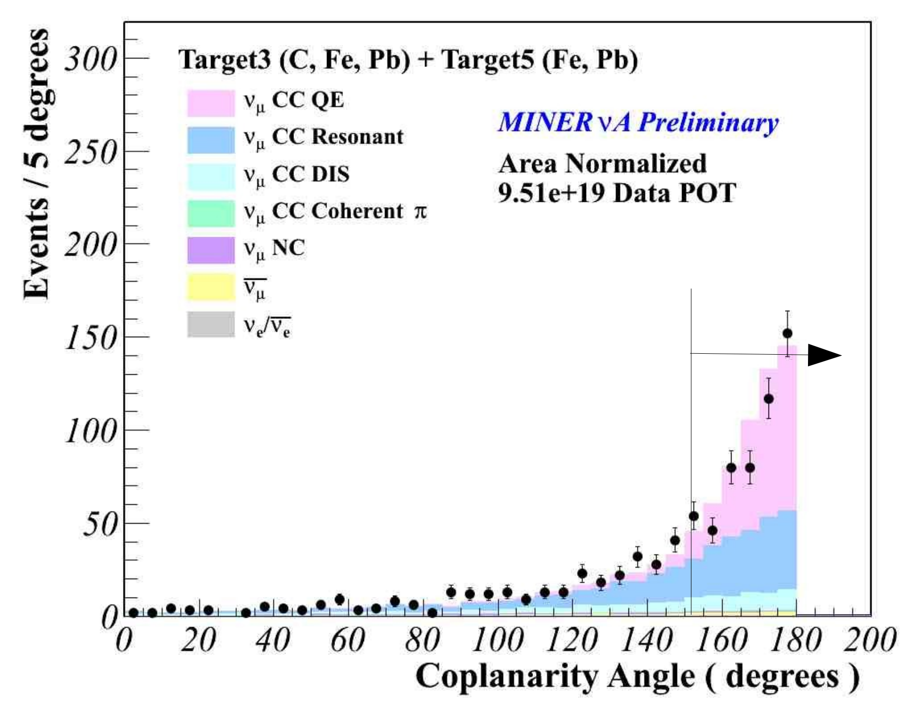
Selecting the Sample

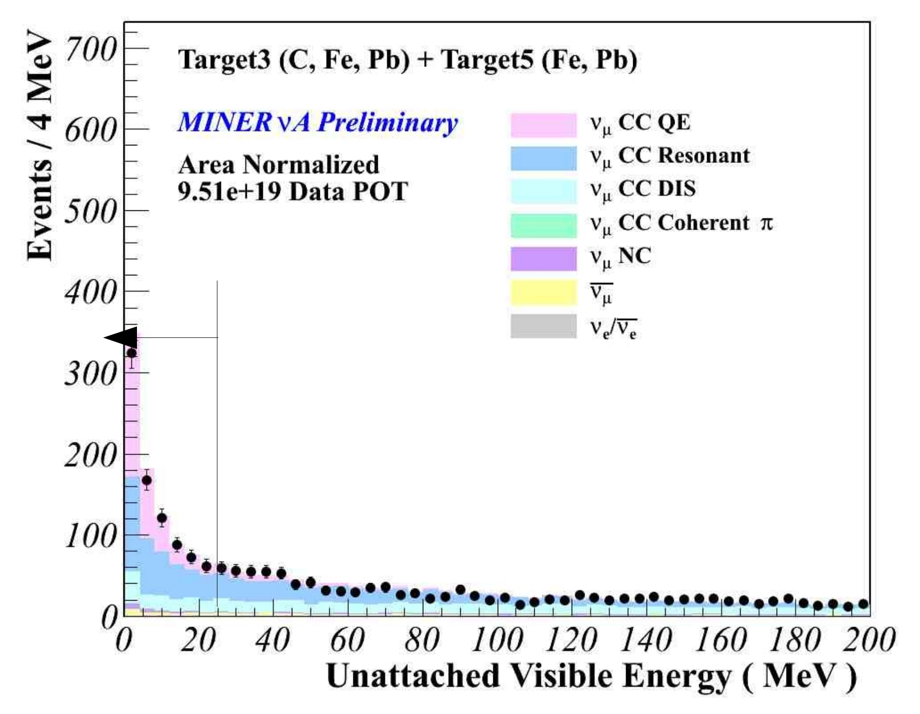
- Require two tracks with common vertex in a nuclear target
- Require one contained and one exiting track
- Make several cuts on the certainty of proton identification



Selecting the Sample

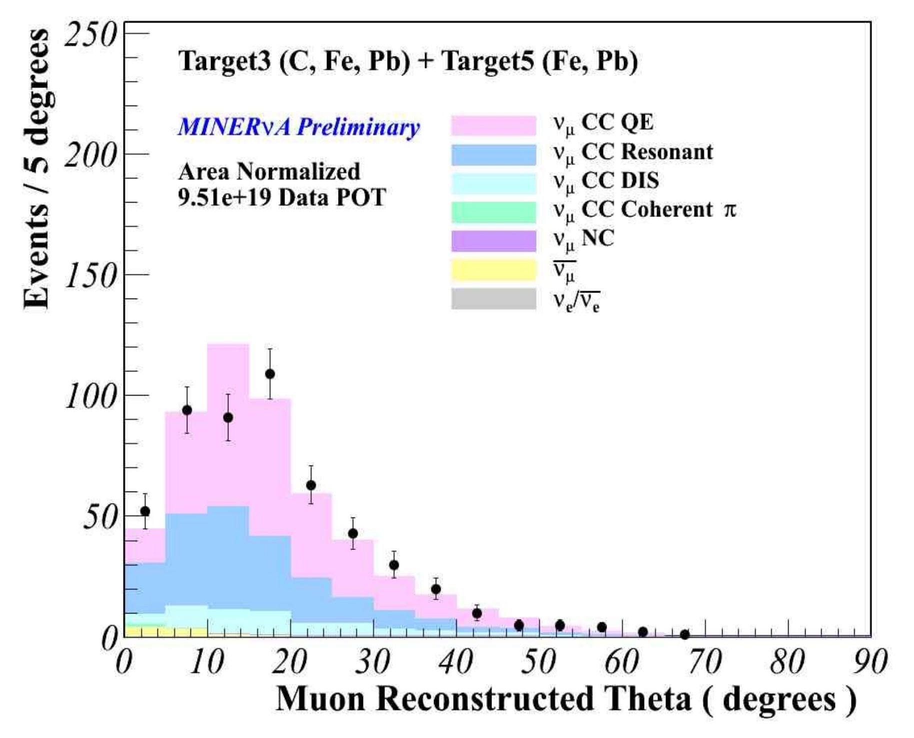
- Muon and proton should be roughly back to back in the rest frame, make coplanarity cut of 150 degrees
- Expect little calorimetric energy in the detector, make a cut at 25 MeV visible energy in the detector

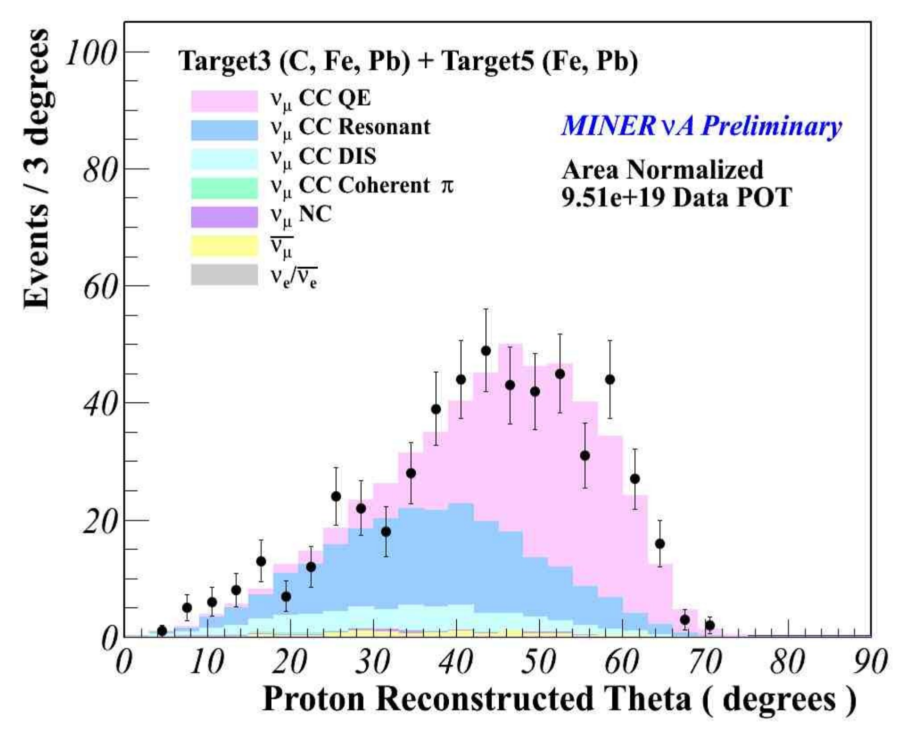




Two Track CCQE Events

- We have isolated our first sample of CCQE events on multiple nuclear targets
- Next step will be to do a multivariate analysis to maximize purity





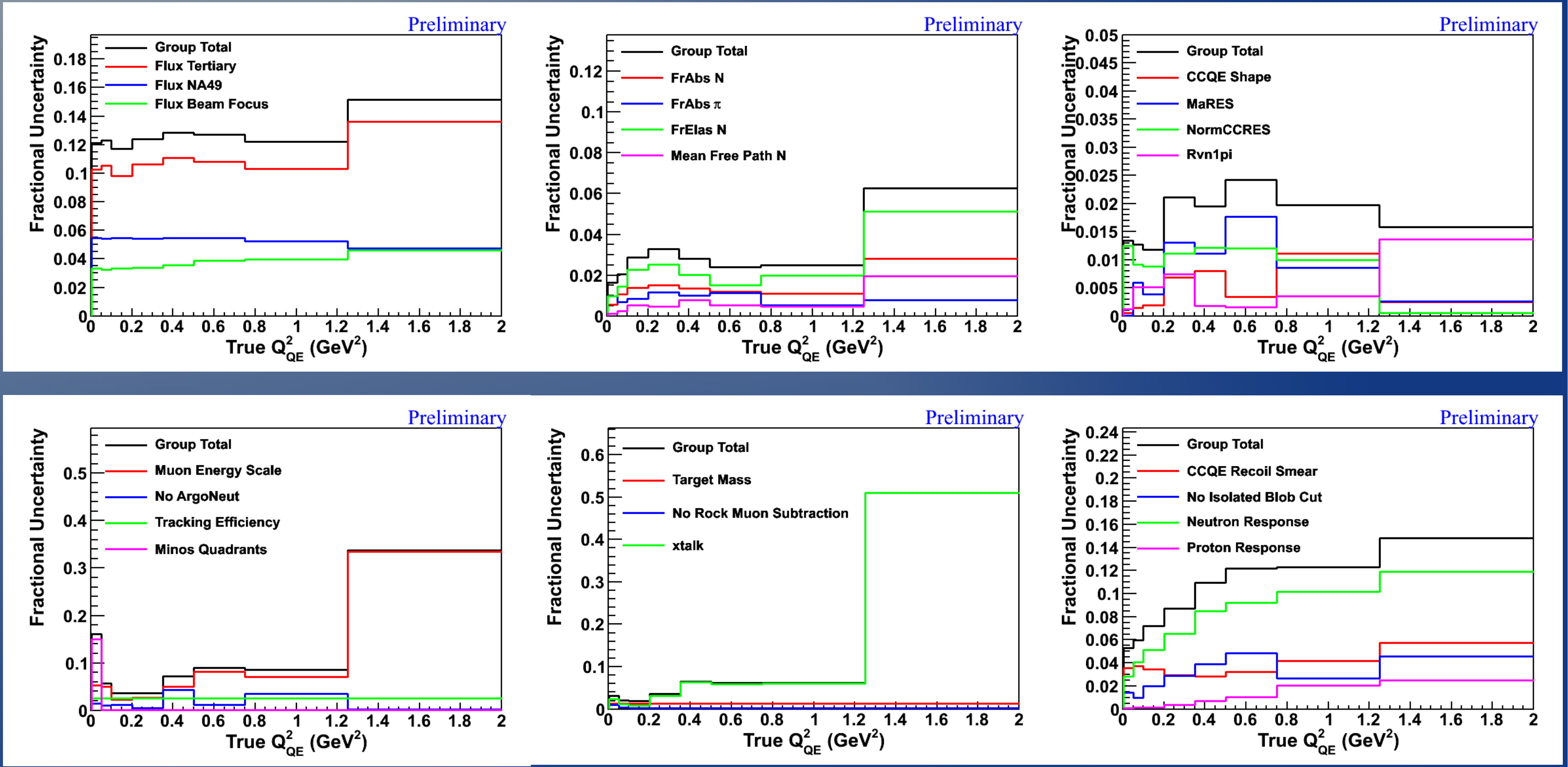
Conclusions

- We have several ongoing CCQE analyses that will measure few GeV cross-sections on scintillator and on different nuclear targets
- We have extracted $d\sigma/dQ^2_{QE}$ for $\bar{\nu}_\mu$ CCQE events
- Each analysis is only on a portion of our total data set, we will incorporate the rest of data soon
- Expect more results soon

Back Up

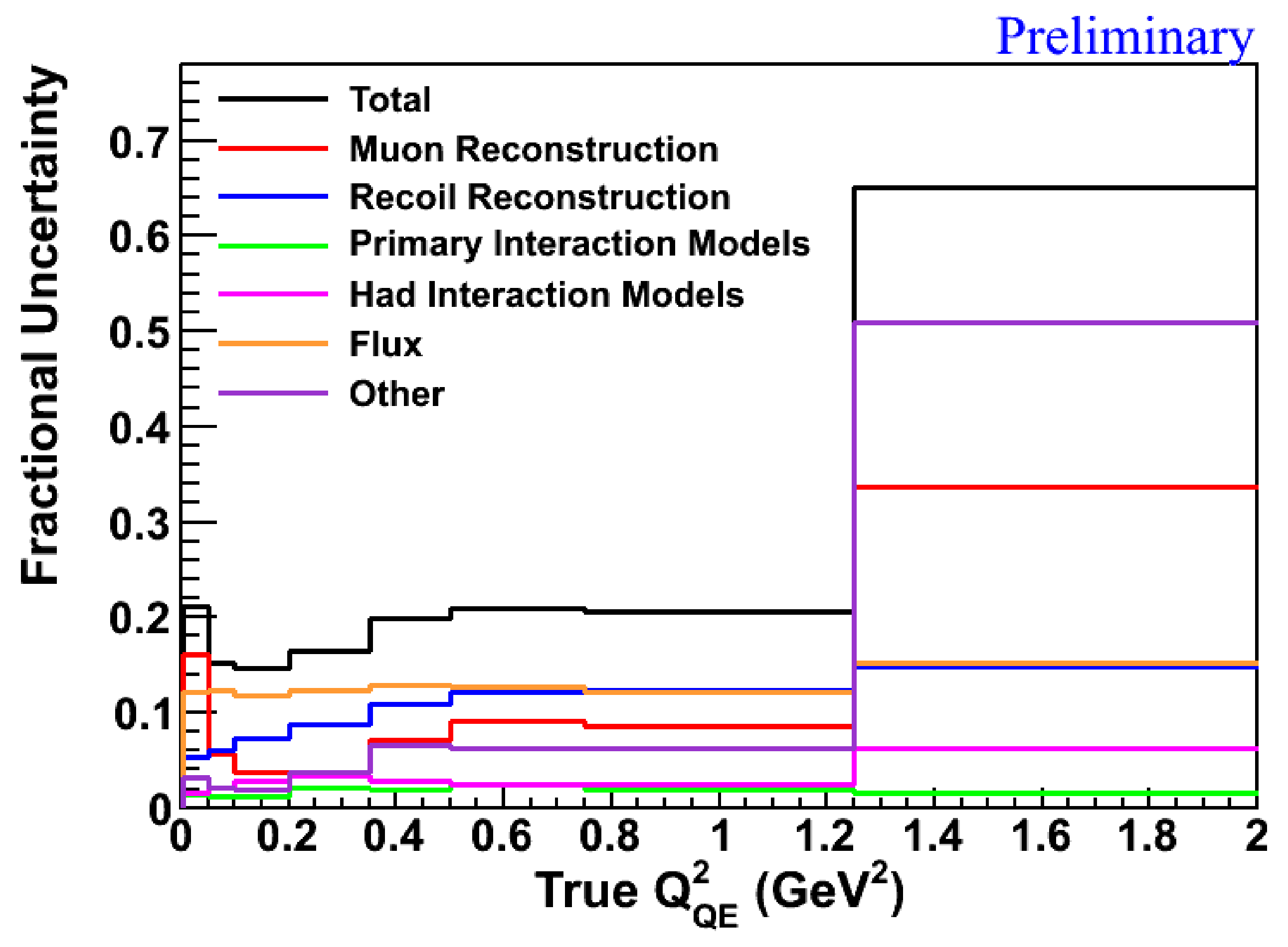
Systematic Errors ($\bar{\nu}_\mu$ CCQE)

- Breakdown of different error components



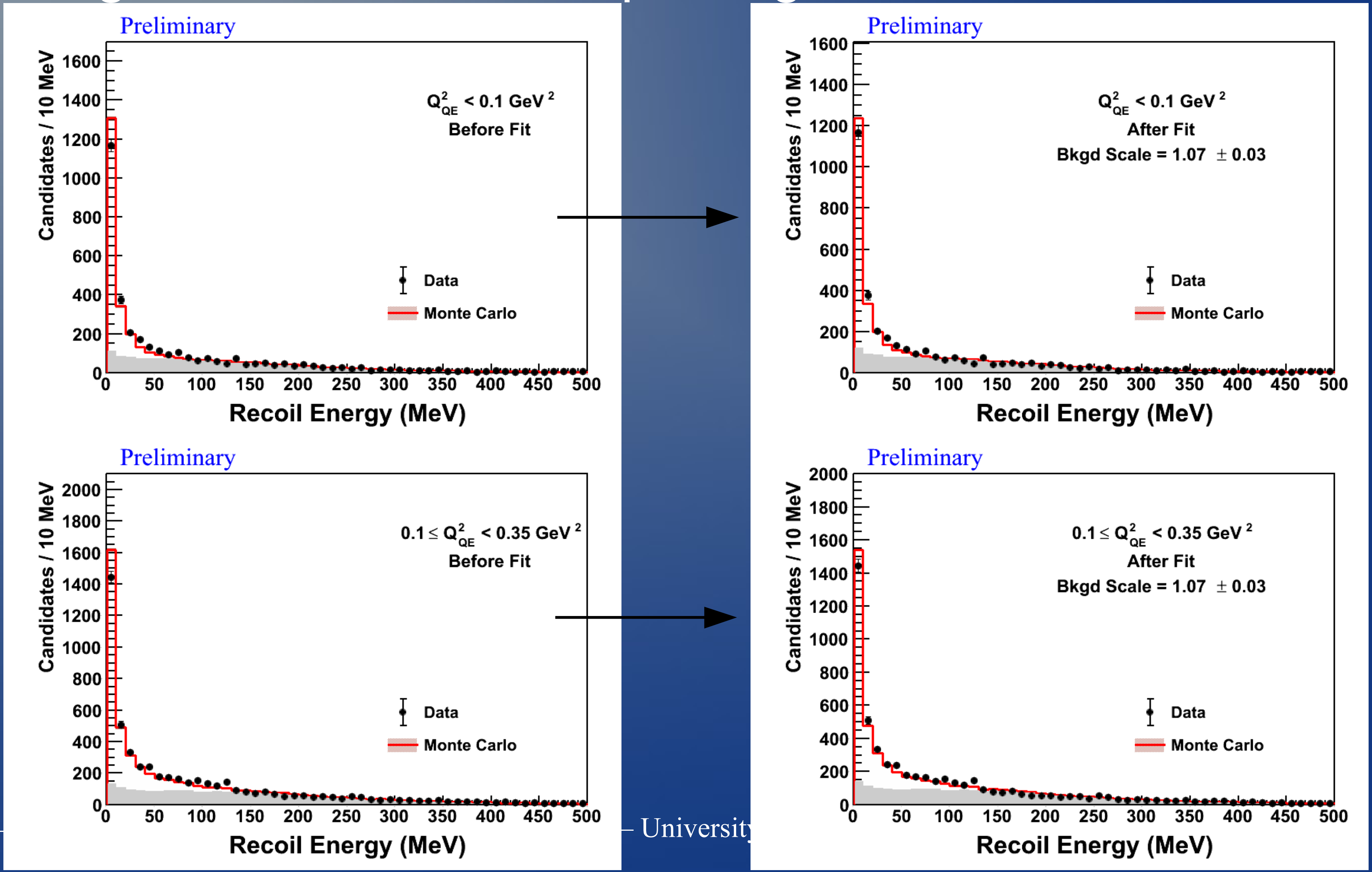
Systematic Errors ($\bar{\nu}_\mu$ CCQE)

- Summary of error by general type

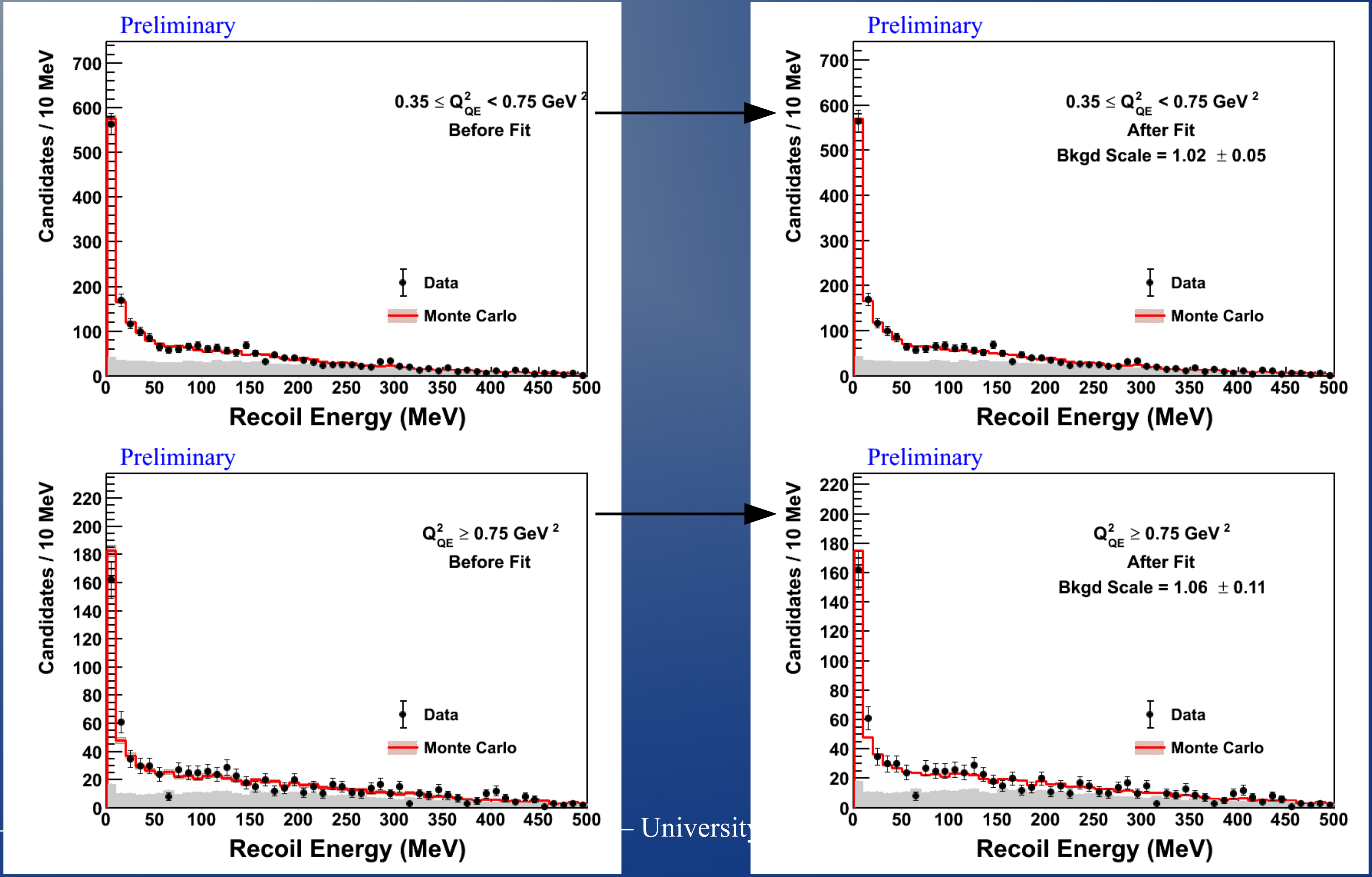


Fitting Background ($\bar{\nu}_\mu$ CCQE)

- Background is found by doing a template fit to data using the TFractionFitter package in ROOT



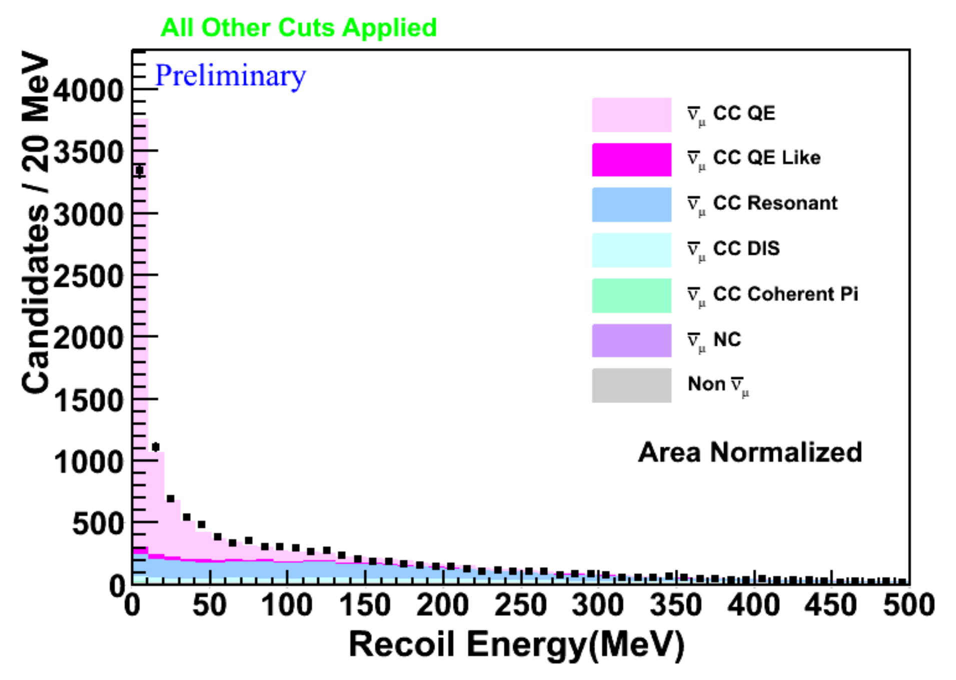
Fitting Background ($\bar{\nu}_\mu$ CCQE)



Selecting a $\bar{\nu}_\mu$ CCQE Sample

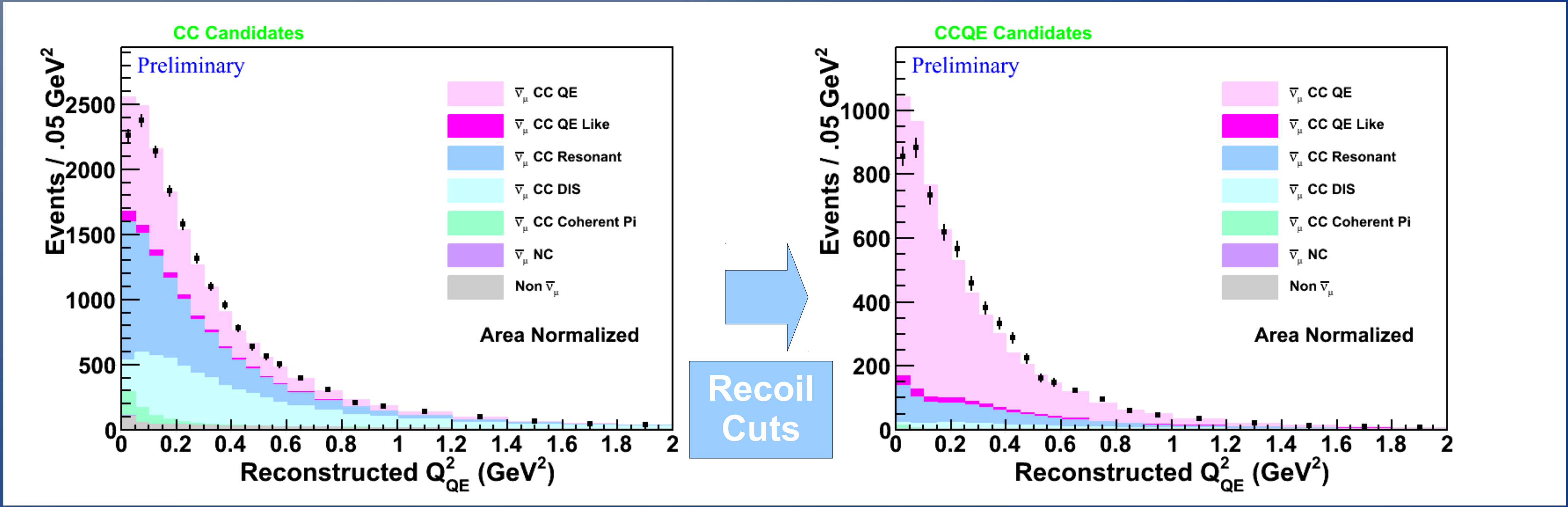
Recoil energy is defined as visible energy in the tracker and ECAL regions of the detector, but excluding:

- Energy near the vertex
- Cross-talk energy deposits
- Energy deposits < 1 MeV
- Energy deposits more than 25 ns away from the muon track time



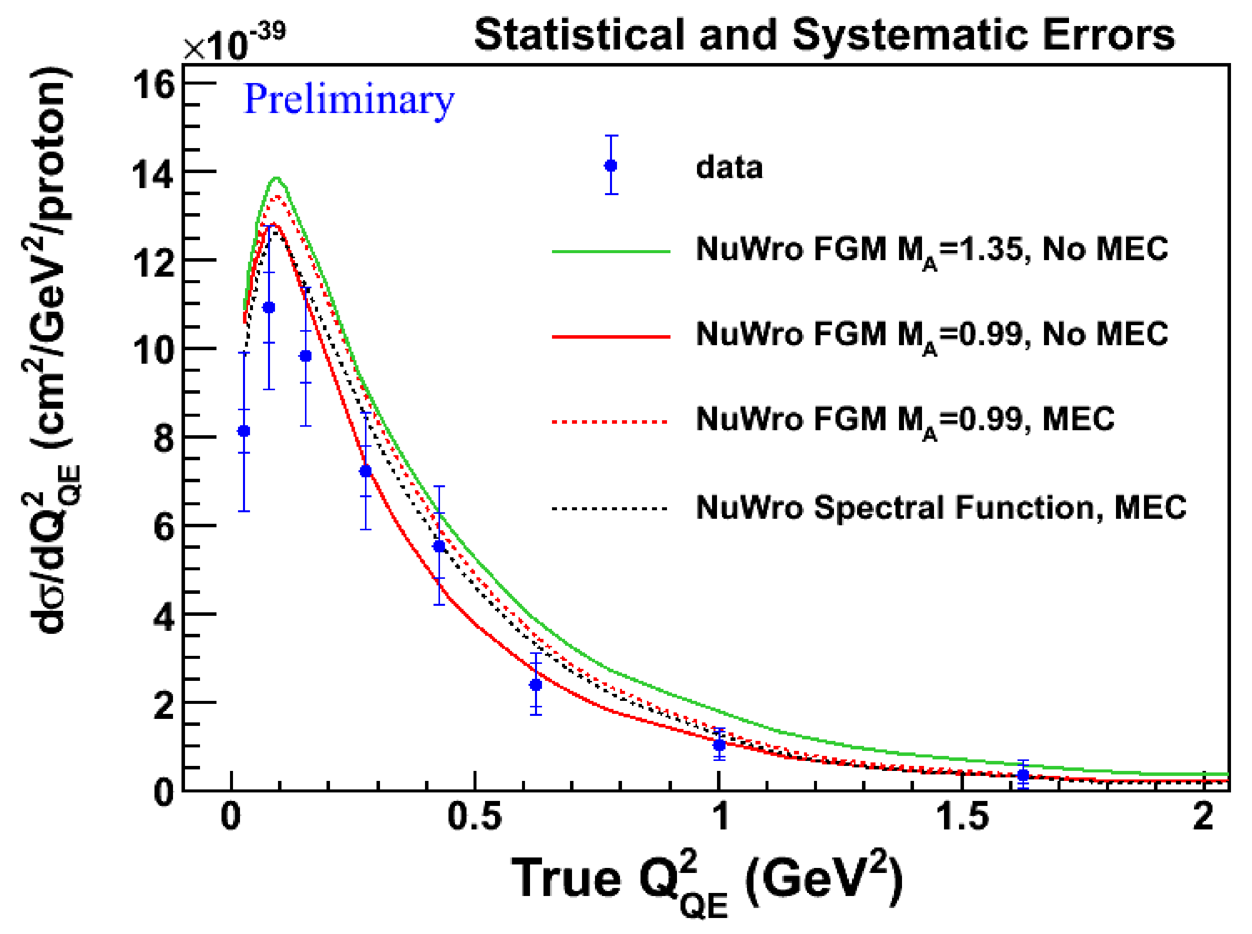
$\bar{\nu}_\mu$ CCQE Sample Before and After Recoil Cut

- Recoil cut is very effective at selecting a very rich quasi-elastic sample



$\bar{\nu}_\mu$ CCQE, Comparisons to Other MC Models

- We find our data is consistent with an MC sample with M_A = 0.99 GeV



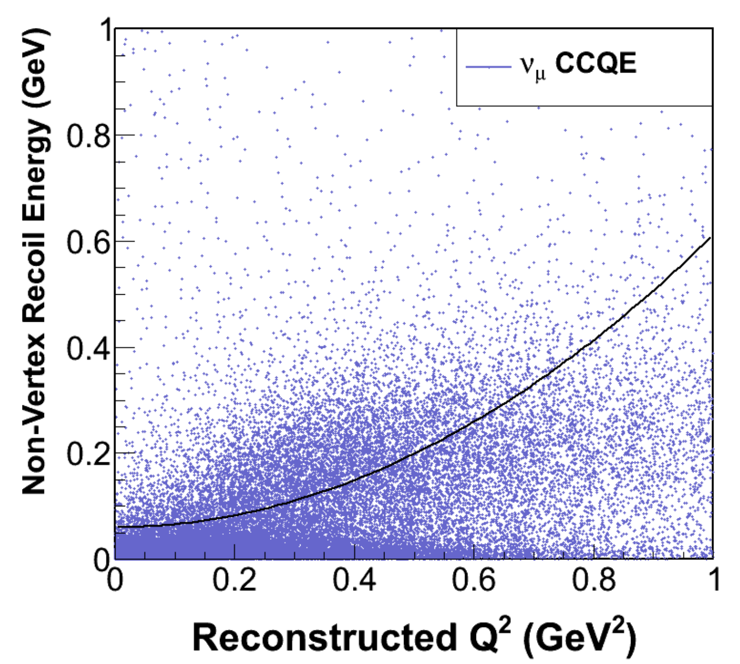
Statistical and Systematic Errors

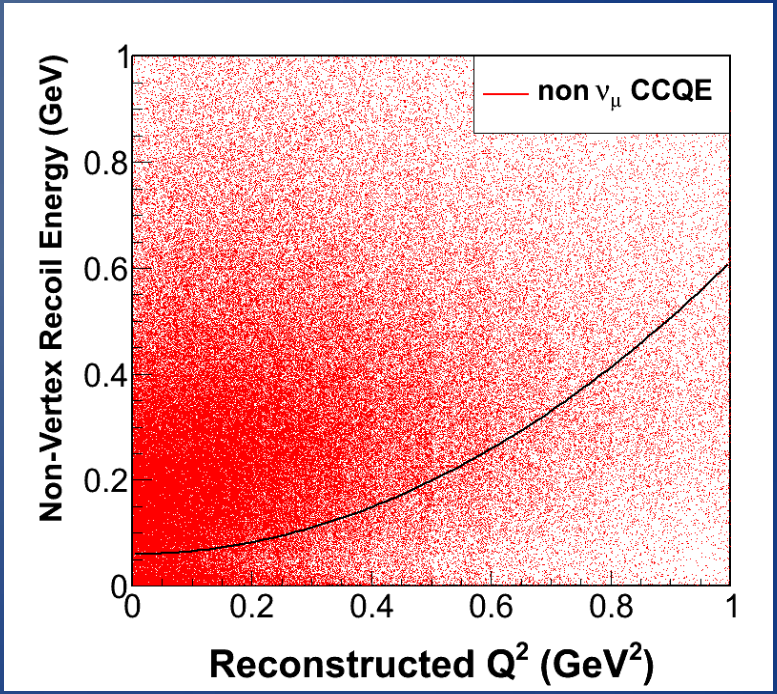
NuWro: Acta Phys.Polon.B40:2507-2512,2009 (http://arxiv.org/abs/0909.1492)

Single Track ν_μ on Scintillator Backup

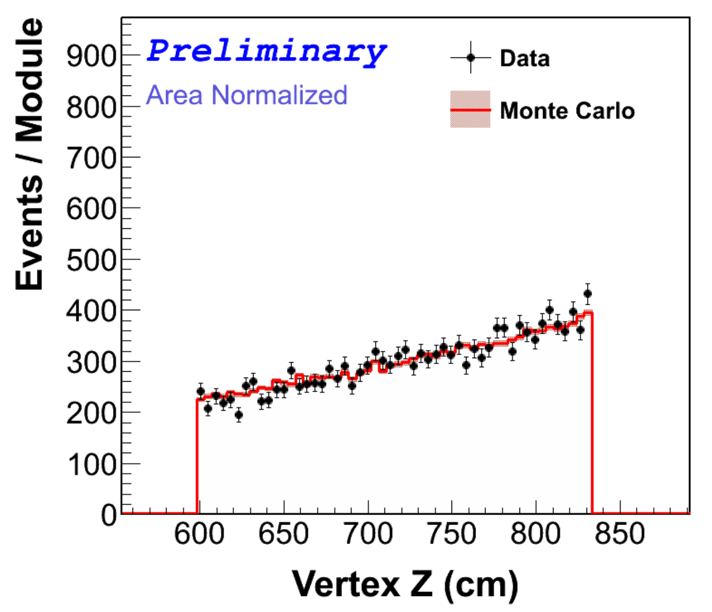
Cut on Recoil

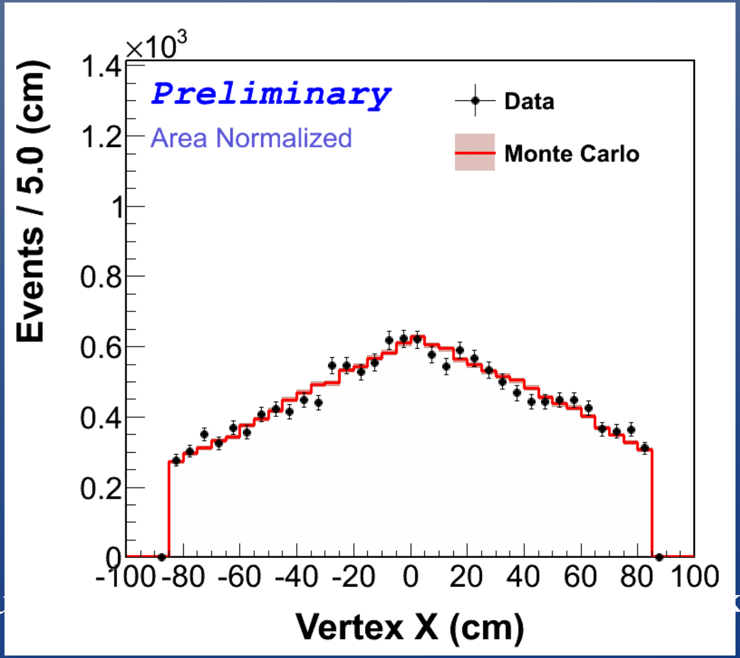
- Recoil energy v. Q^2 for signal and background

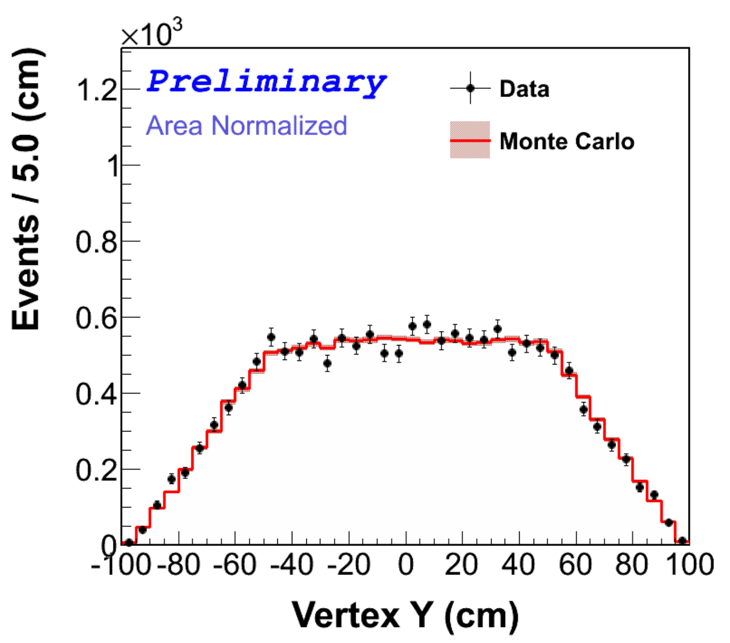




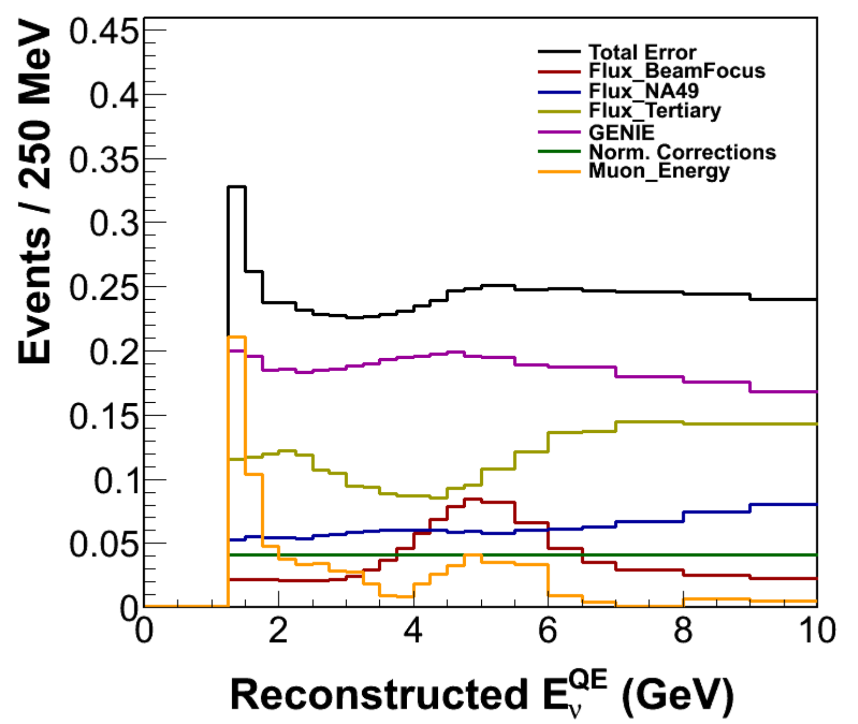
Single Track Vertex Distributions

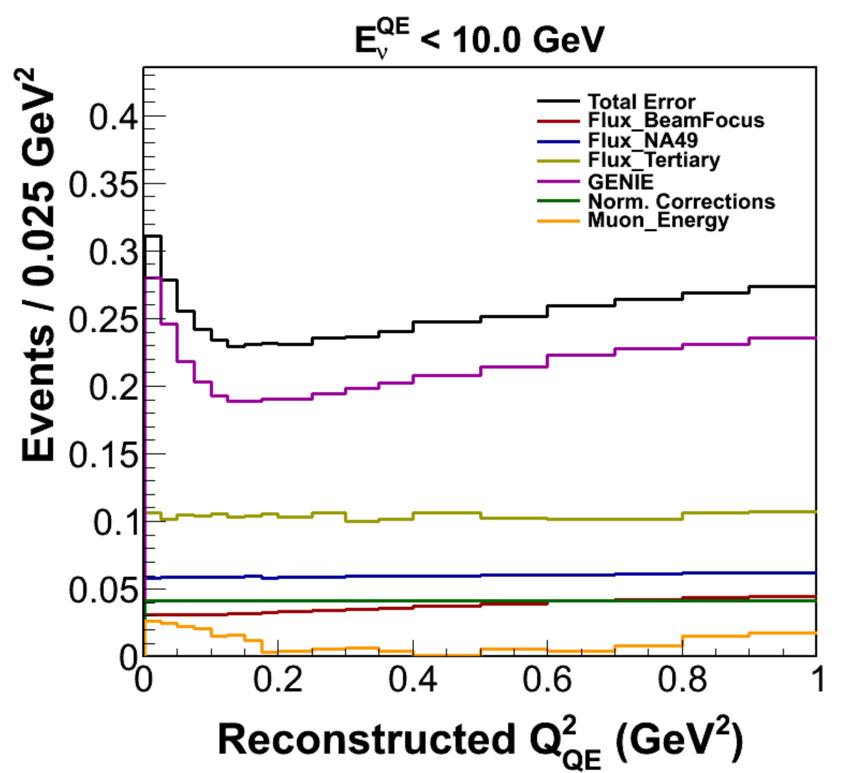






Systematic Error by Type



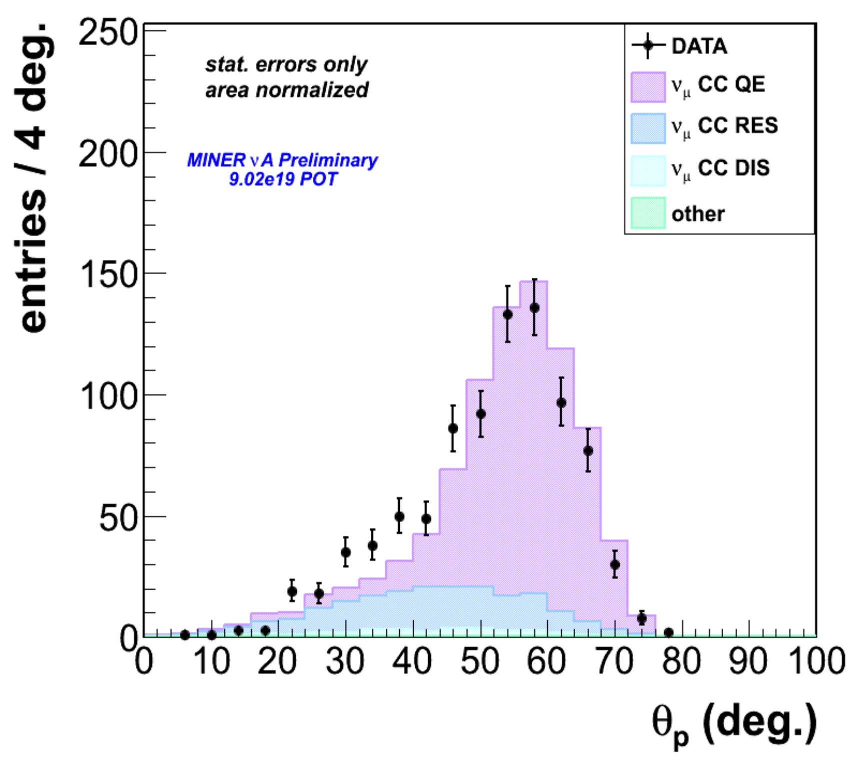


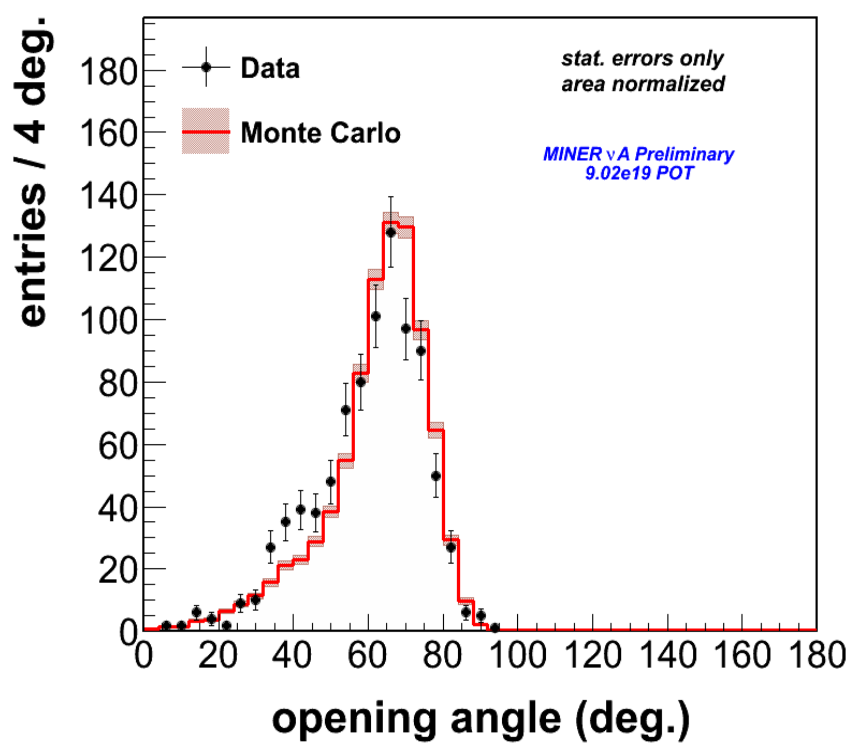
Two Track ν_μ CCQE on Scintillator Backup

ΔKE

- $\Delta KE = (E_{\nu}^{CCQE} - E_{\mu} - E_{b} - E_{p})/E_{p}$
- Eb = 30 MeV
- $-0.3 < \Delta KE < 1.5$

Angular Distributions

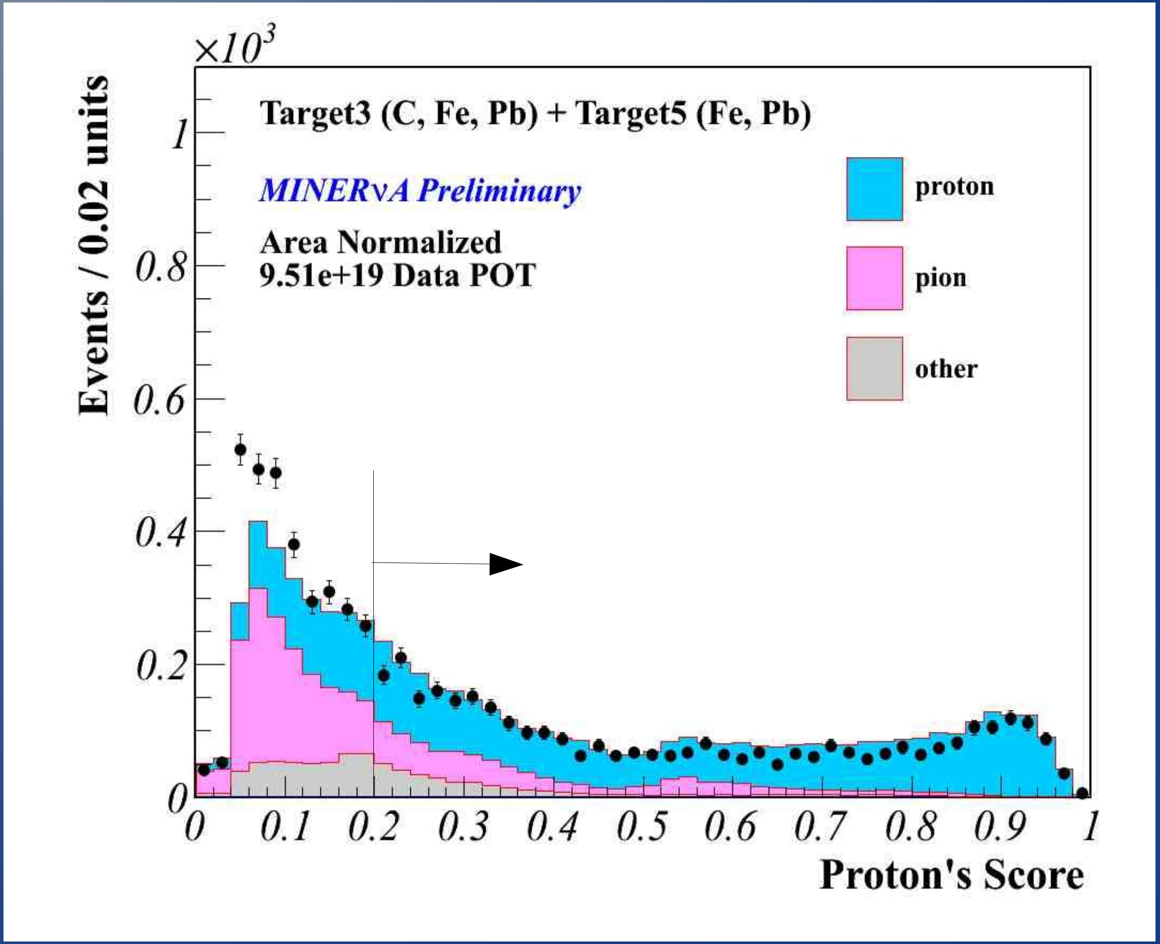




Two Track ν_μ CCQE on Nuclear Targets Backup

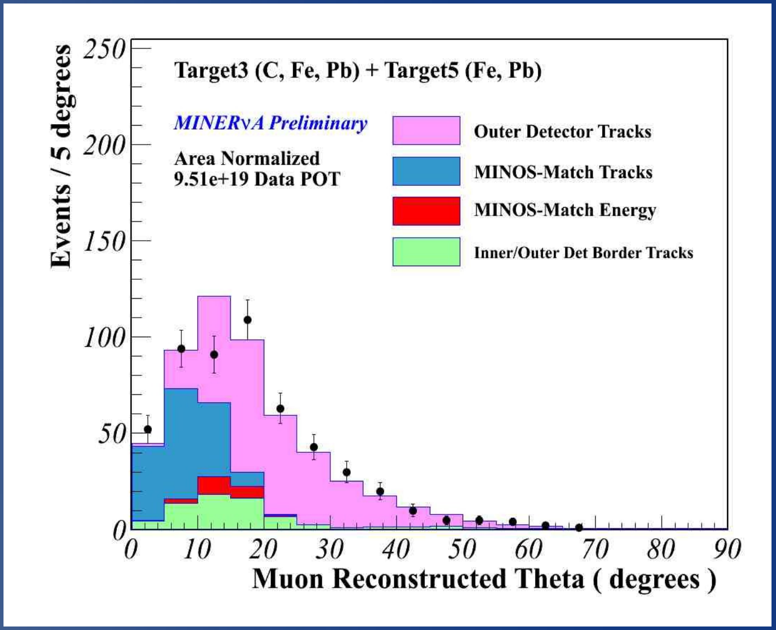
Proton Cut

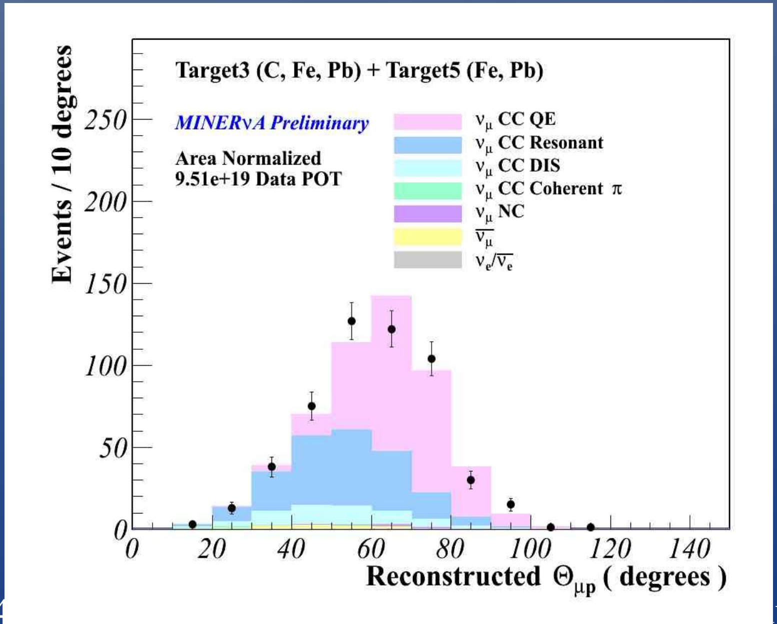
- Cut on proton score, > 0.2

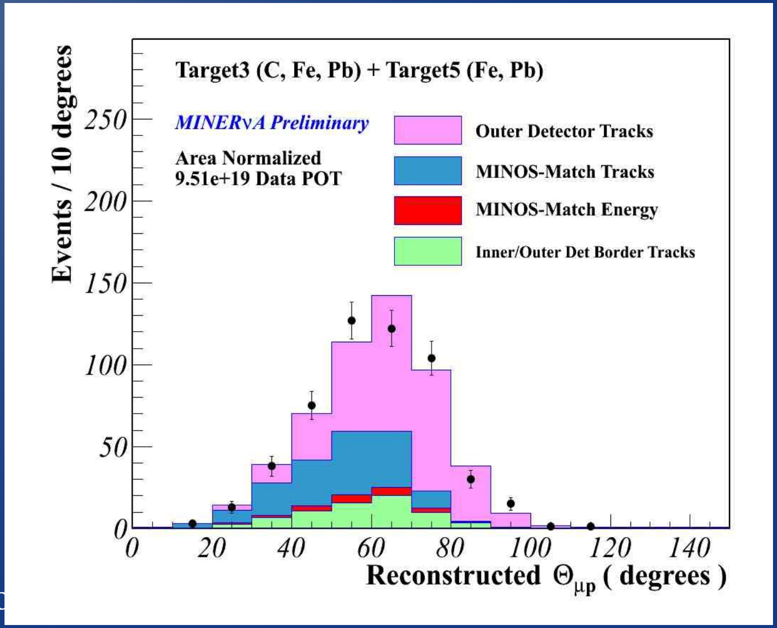


Two Track Nuke Events

- Measuring the opening angle between the muon and proton can give us a window into final state interactions

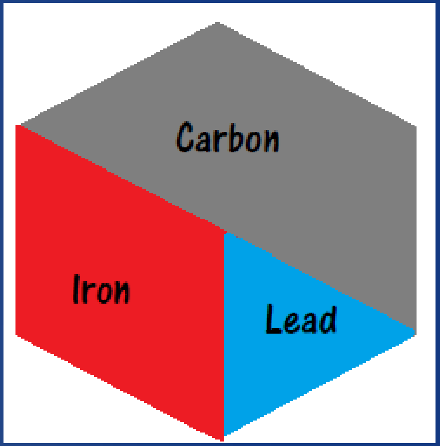


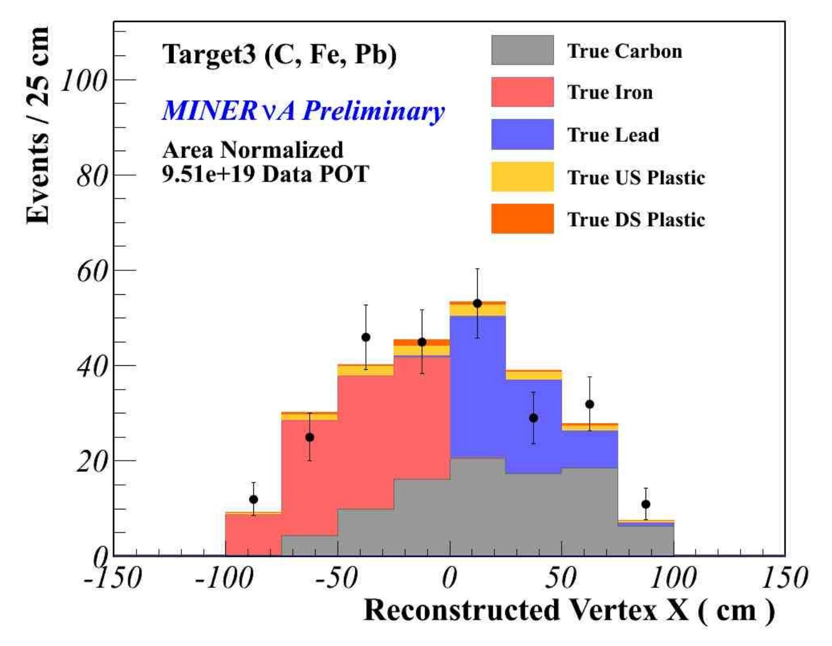


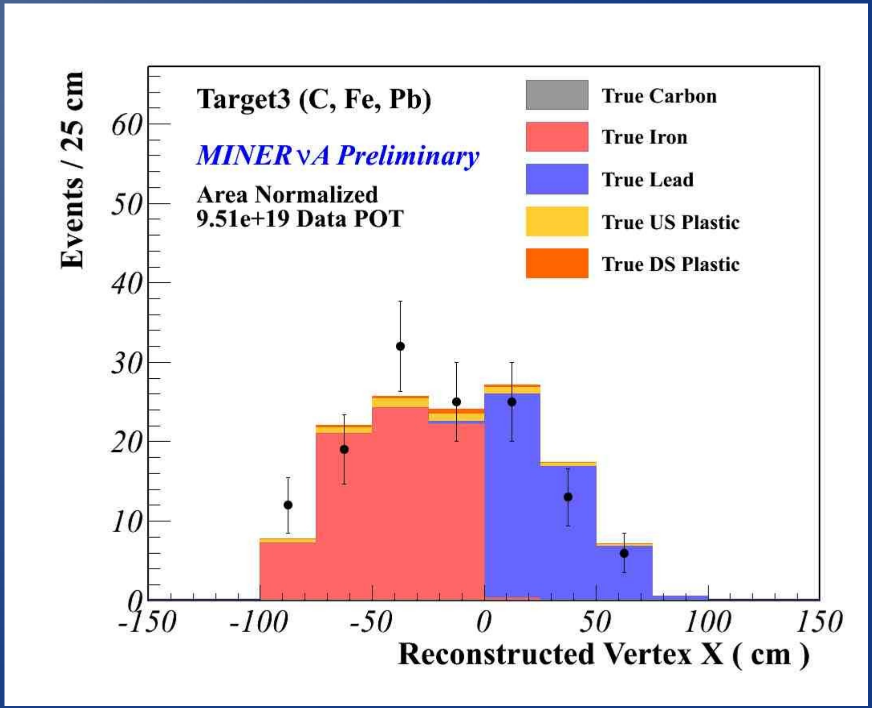


Two Track CCQE Events

- Define C-axis to clearly separate events with a vertex in the carbon targets from

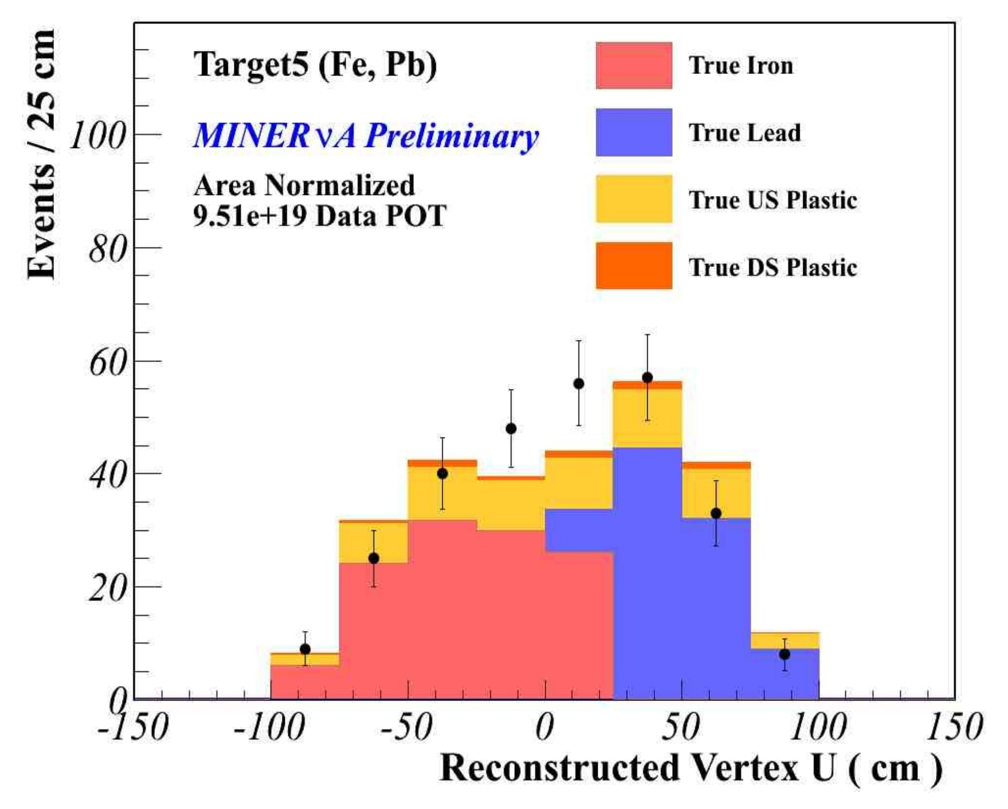


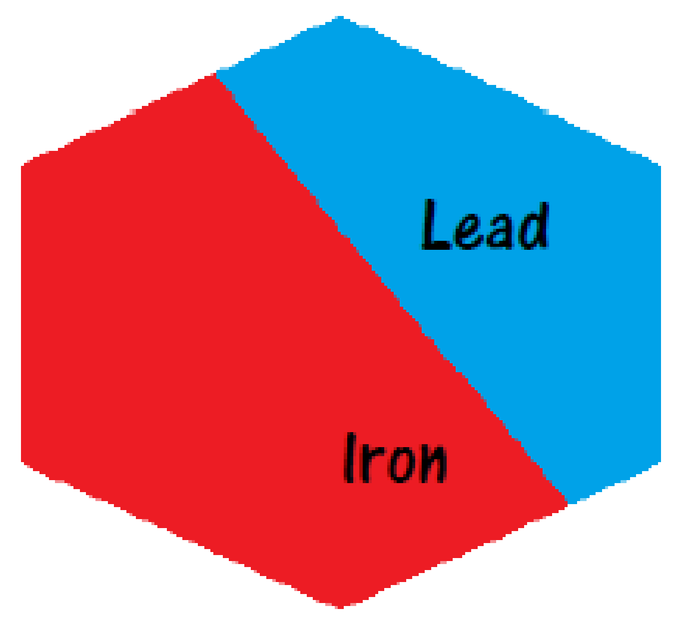




Two Track CCQE Events

- Define U axis so regions of Nuclear Target 5 are clearly separated





NuMI Beam Flux Details

- ~35 E12 POT per spill
- Spill length/frequency = 10 μs/0.5 Hz
- Beam power: 300-350 kW

GENIE Generator Details

For QE Generation, specific details of model are:

- Used GENIE 2.6.2 with M_A = 0.99 GeV
- General equation is Llewellwyn-Smith (with lepton mass terms)
- The pseudo-scalar form factor is taken from PCAC
- Electromagnetic form factors are BBBA2005 (hep-ex/0602017)
- The nuclear model is a fermi gas, with a high momentum component included (taken from Bodek and Ritchie - Phys.Rev. D23 (1981) 1070)
- Pauli blocking is applied by requiring the outgoing nucleon has momentum above the fermi momentum for the nucleus in question, 221 MeV/c for carbon

Meson Exchange Currents

- Proposed to account for cross-section disagreement between MiniBooNE/SciBooNE and NOMAD

  (A. Bodek, H.S. Budd, M. E. Christy, 2011: http://arxiv.org/abs/1106.0340)

- Alters cross-section due to a correction to magnetic form factors in the cross-section calculation