Anti-Neutrino Quasi-Elastic Scattering in MINERvA

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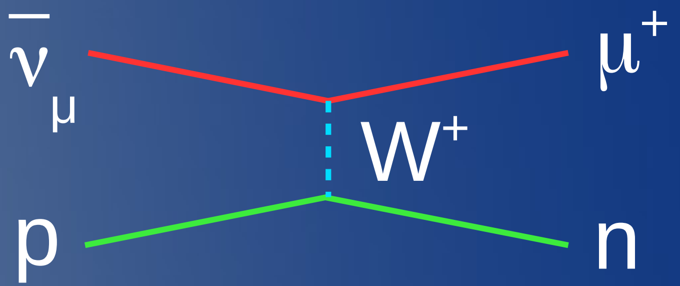
Overview

- Description of Quasi-Elastic (QE) Scattering
- Physics Motivation
- The NuMI Beam and MINERvA Detector
- Results
- Outlook

What is Quasi-Elastic Scattering?

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



- Neutron is ejected from the nucleus, but not necessarily observed
- Incoming neutrino energy and momentum transfer can be reconstructed with just the muon kinematics

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

$$M_p' = m_p - \varepsilon_B$$

$$\varepsilon_B = 30\ MeV$$

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

Uses Relativistic Fermi Gas Model (RFGM)

Quasi Elastic Cross Section

- Cross section calculated using a variety of form factors (vector and axial vector)
  - Vector form factors extracted from electron-proton scattering
  - Axial vector form factor (Dipole Approximation shown below) must be 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

- Uncertainties on neutrino interaction cross sections are a significant systematic error for neutrino oscillation experiments
- Quasi-Elastic scattering is a particularly useful channel for oscillation measurements
  - Fully reconstruct neutrino energy
  - Flux standard candle
- Recently, MINOS found a discrepancy between neutrino and anti-neutrino oscillation
  - Both neutrino and anti-neutrino cross-sections are needed

The NuMI Beam Line

- Neutrinos created from pion and kaon decays
- Ability to predict pion and kaon production off the target is the largest uncertainty in determining our flux

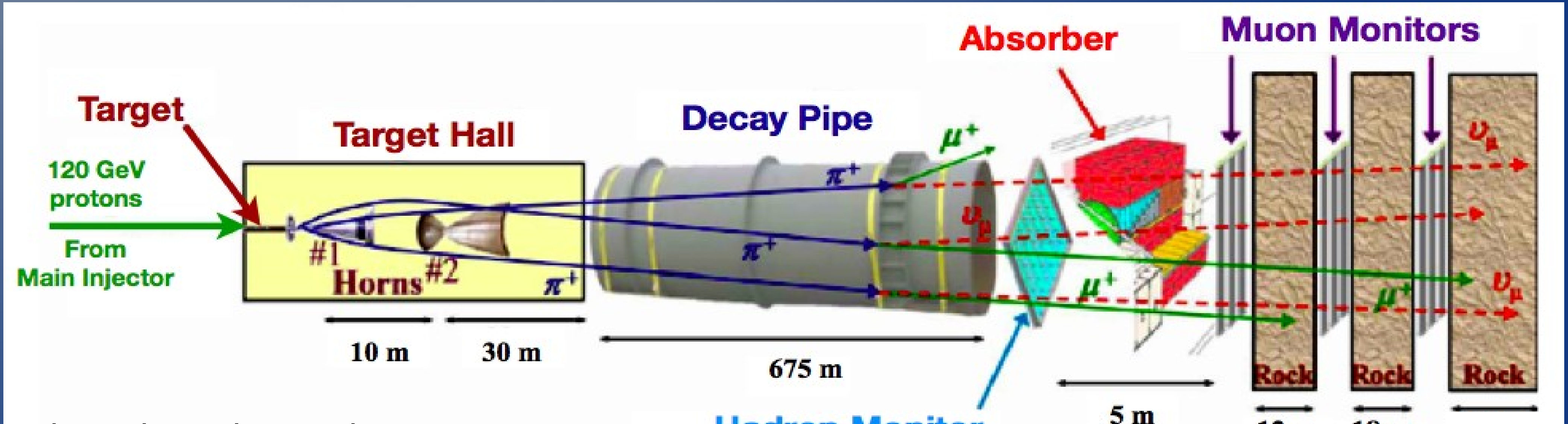
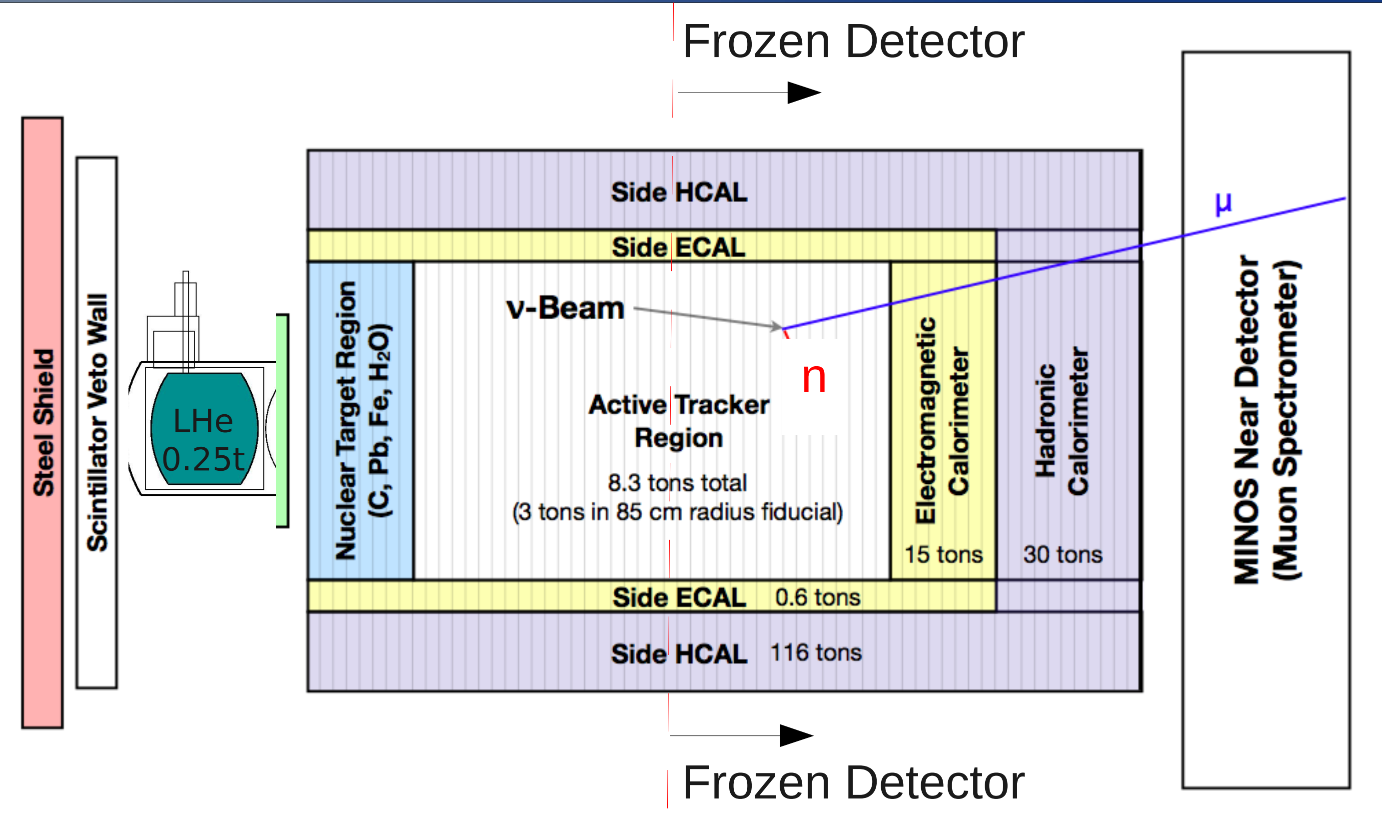


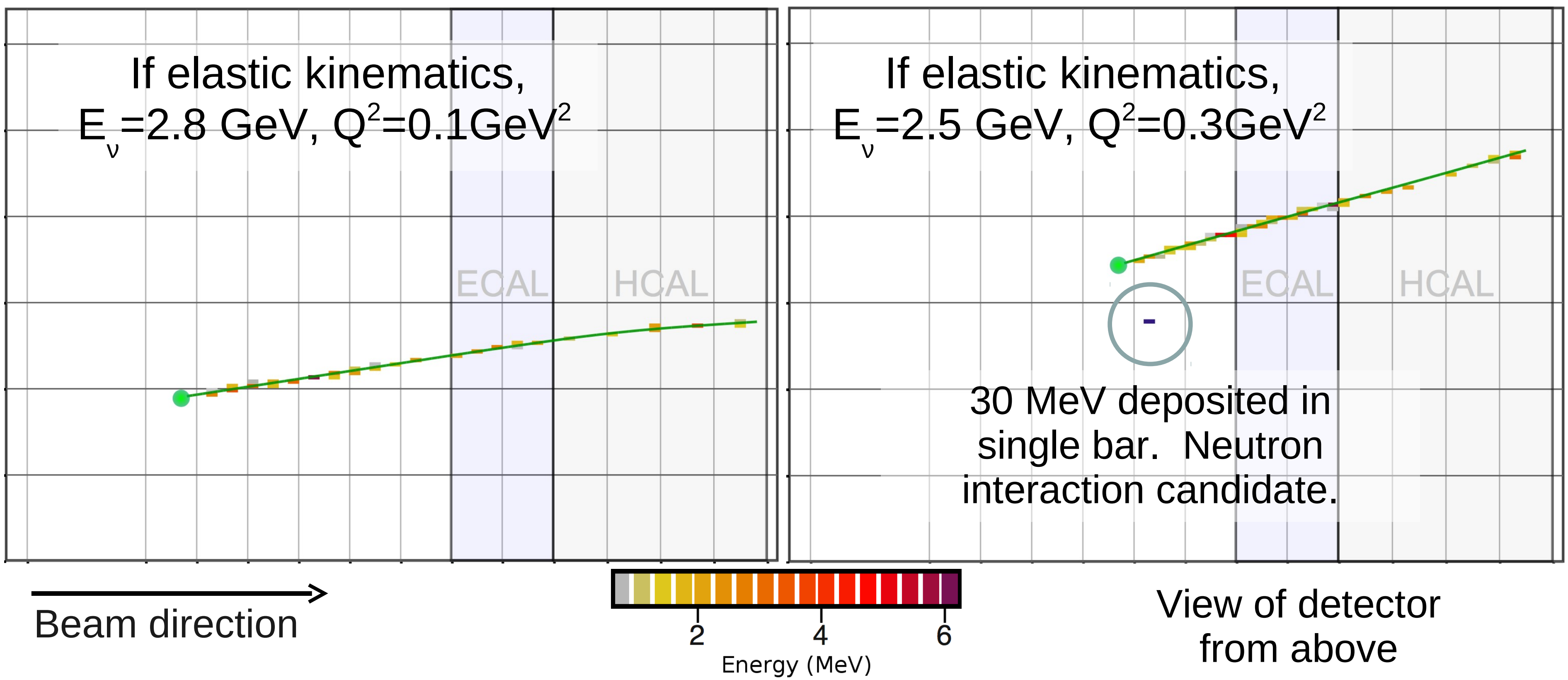
Figure by Bob Zwaska

The MINERvA Detector

- Fine grained detector that lies upstream of the MINOS Near Detector (our muon spectrometer)
- Data that we show is from our partially constructed detector
- We show 4e19 POT worth of anti-neutrino data (~15% of total number of events)

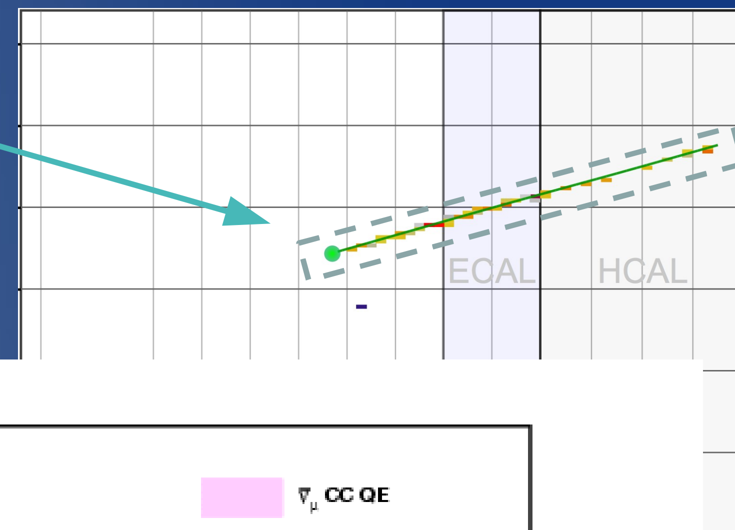


Example of QE Candidate Events in MINERvA (data)

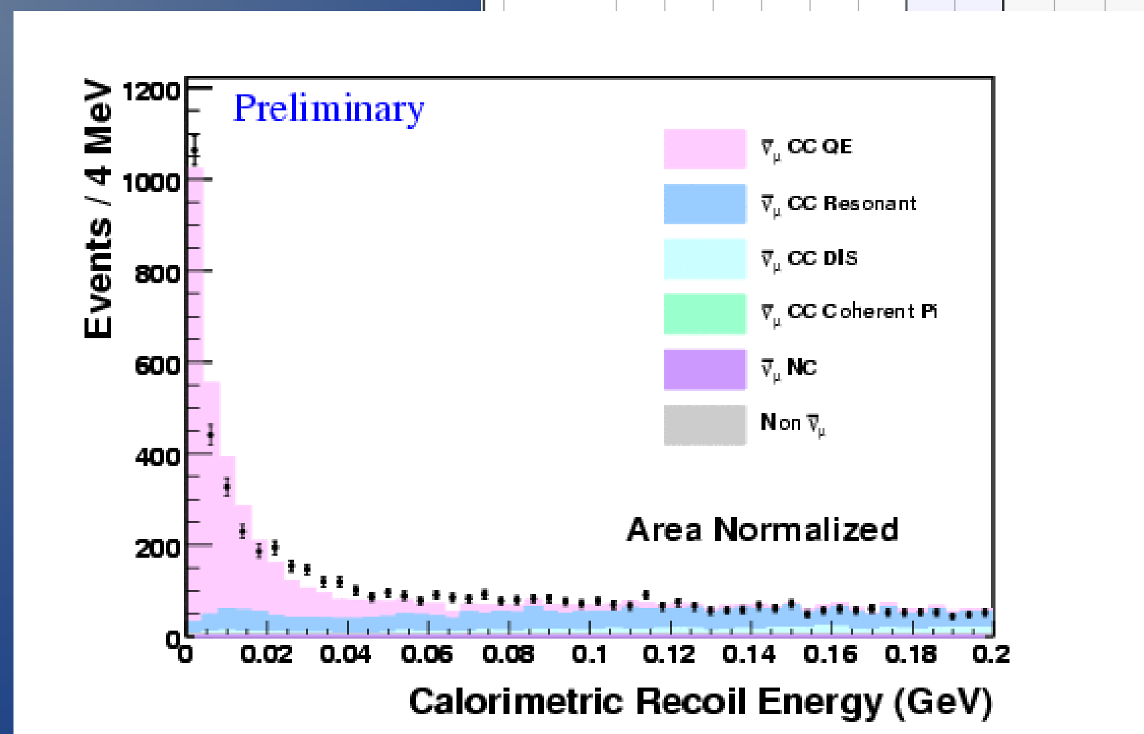


Recoil in MINERvA

- We summed all energy 5 cm away from the muon track and defined this as the recoil energy

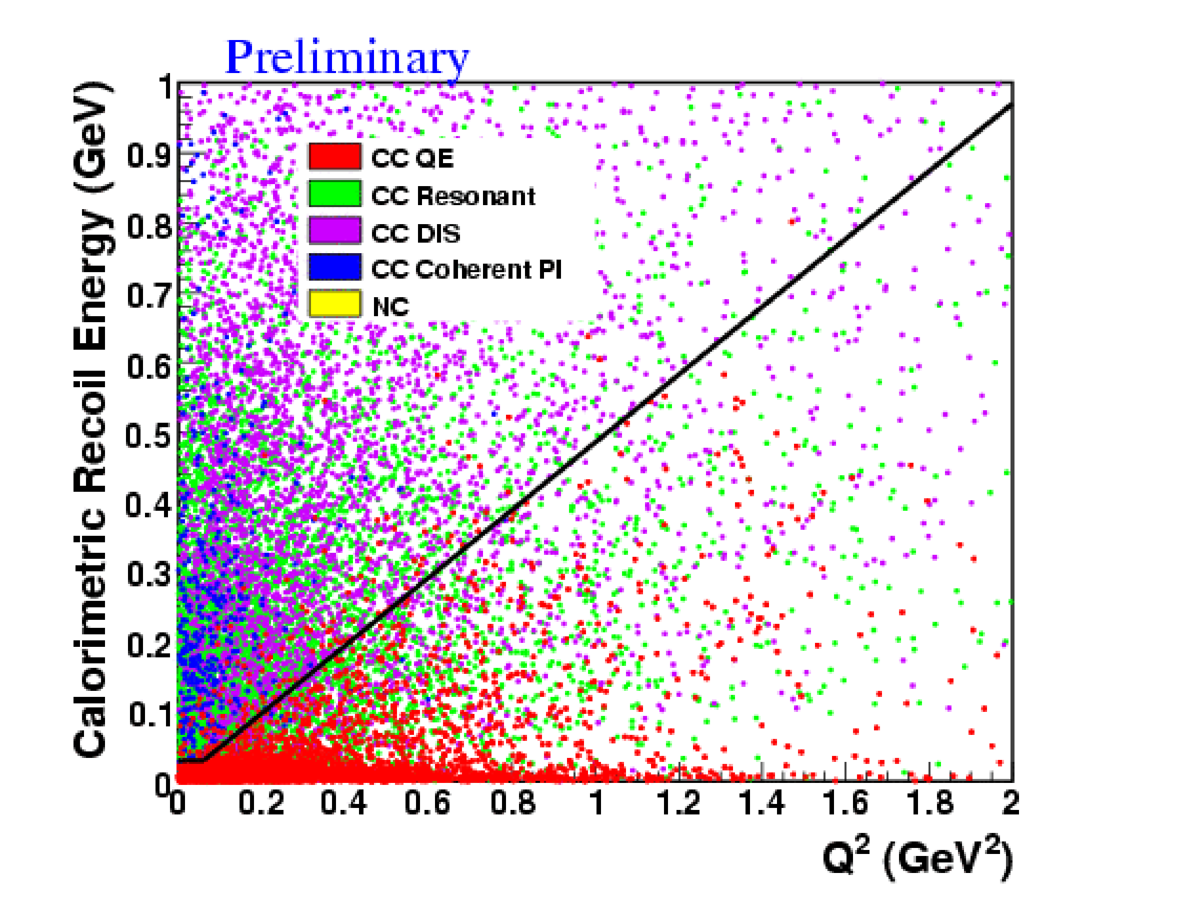


- Found a rich QE sample at low recoil energy
- Found that if we applied a flat recoil cut, we lost a large fraction of QE events at higher Q^2



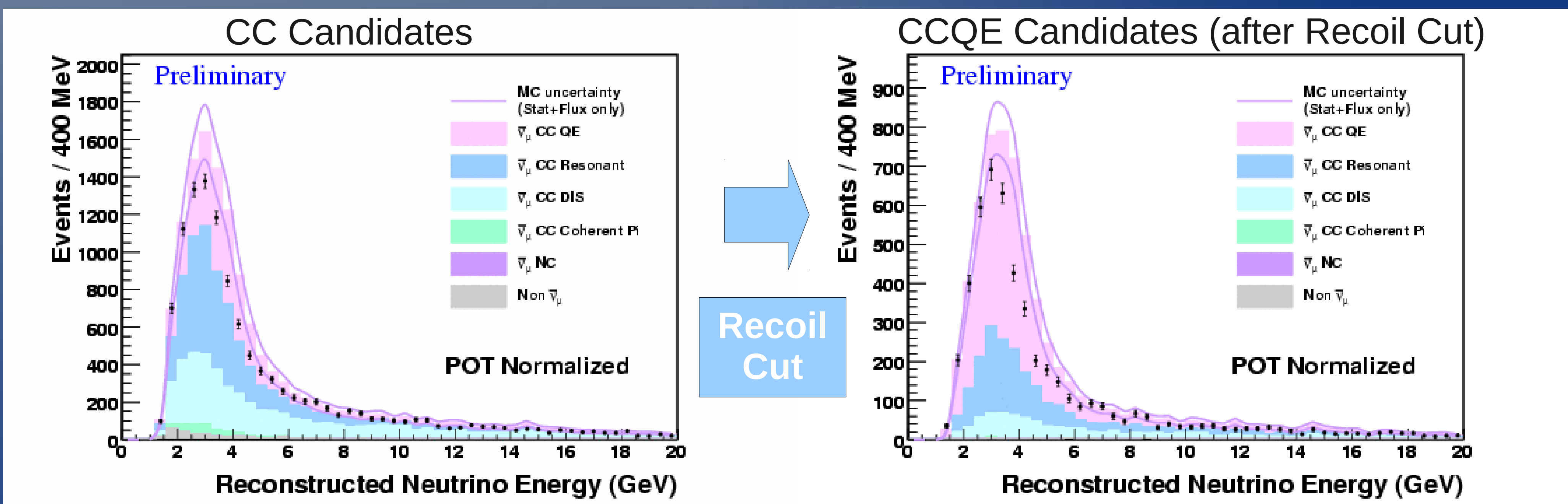
Selecting a QE Rich Sample

- For quasi-elastic scattering, $Q^2 = 2m_p\nu$, where ν is the energy transfer to the hadron
- Expect higher Q^2 events to have more recoil energy
- Made a recoil cut that scales with $Q^2/2m_p$



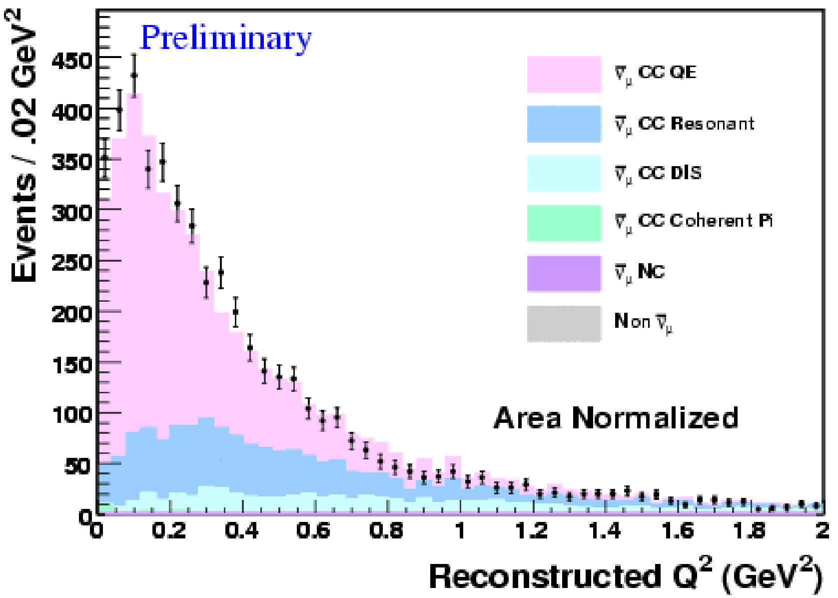
CCQE Sample after Recoil Cut

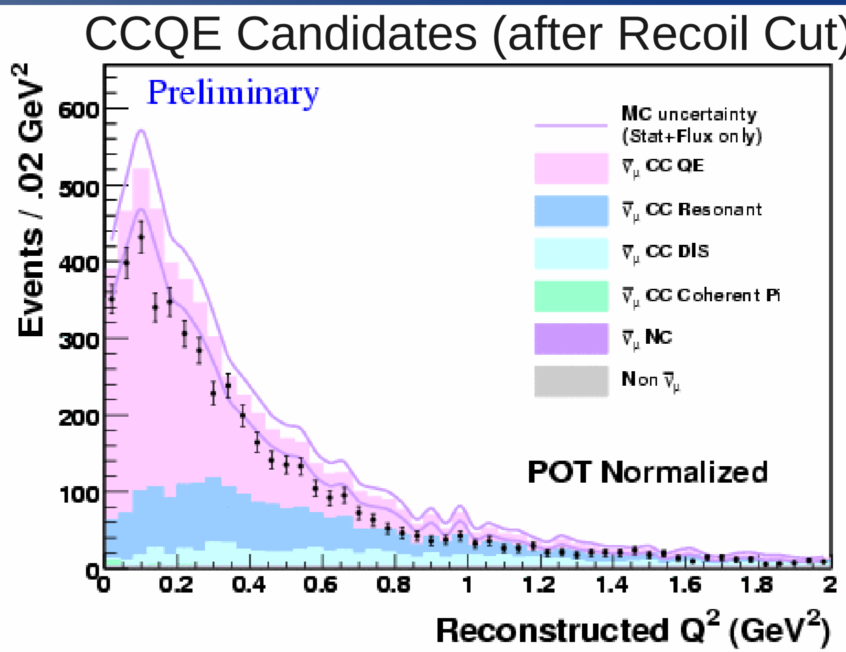
- Distributions are absolutely normalized and include statistical and flux errors
- Recoil cut is very effective at selecting a very rich quasi-elastic sample



Reconstructed Q^2

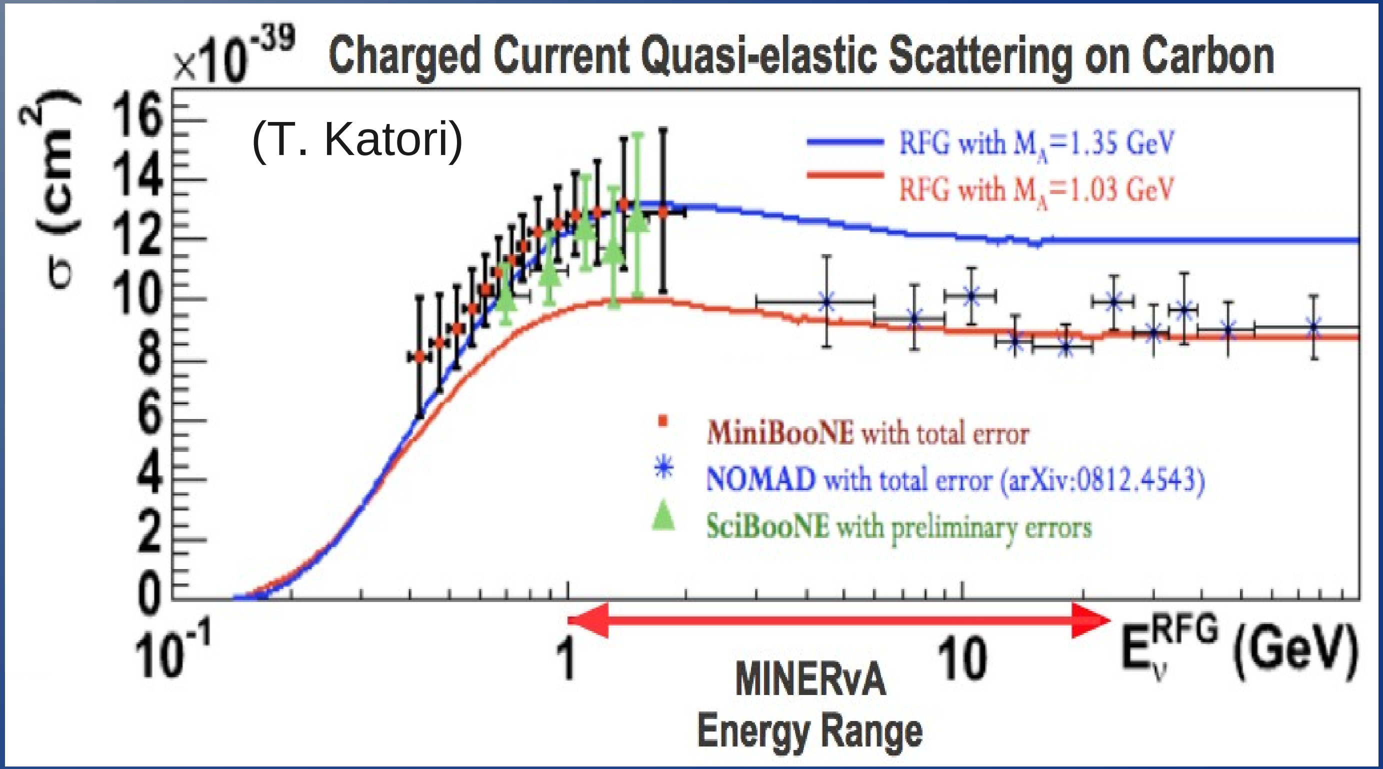
- Have events in a broad Q^2 region, but with more contamination at higher Q^2
- See excess of events in Monte Carlo





Recent World Cross Section Results

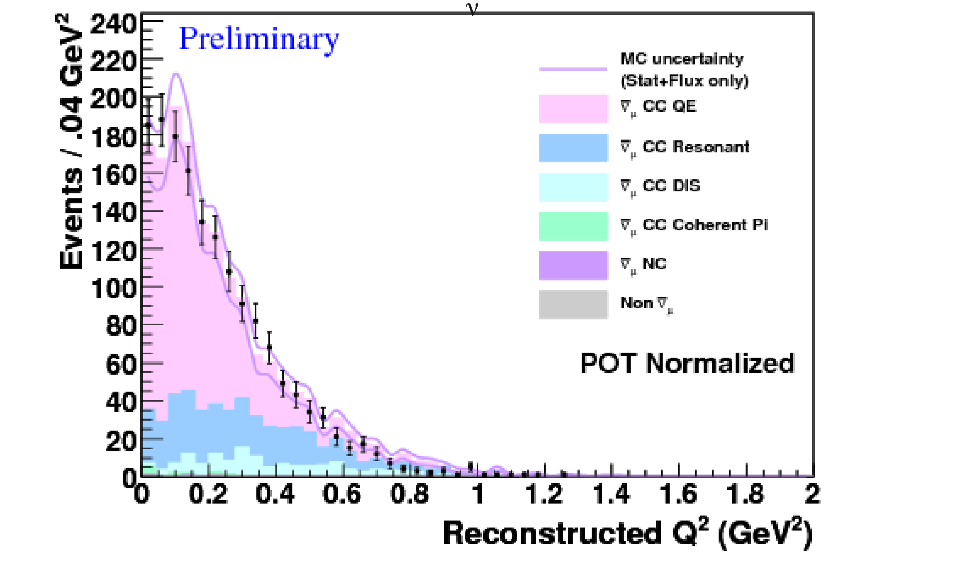
- Tension between various cross-section results
- Our simulation (GENIE 2.6.2) used M_A = 0.99 GeV
- Would M_A = 1.35 GeV found by MiniBooNE fit our data better?



Note: Cross-sections are for neutrinos

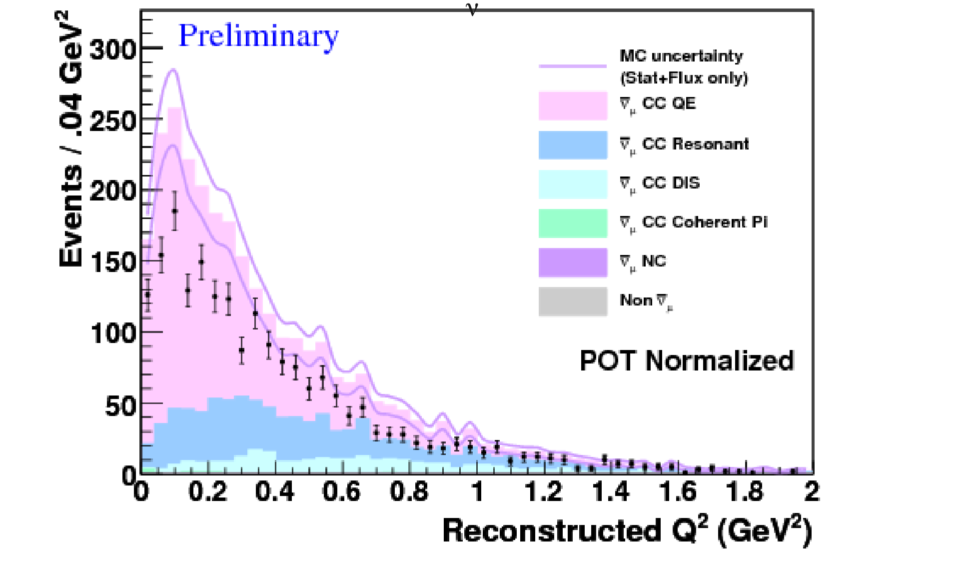
Q^2 Separate by Energy

$1\ \text{GeV} < E_\nu < 3\ \text{GeV}$

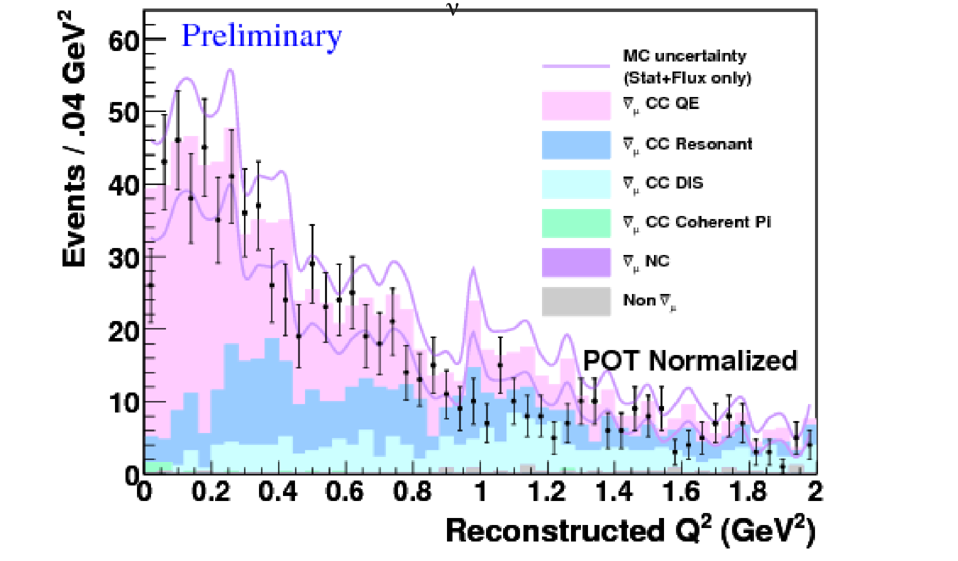


- Most discrepancy comes from the 3-5 GeV region
- For MiniBooNE M_A, expect more events across anti-neutrino energies

$3\ \text{GeV} < E_\nu < 5\ \text{GeV}$

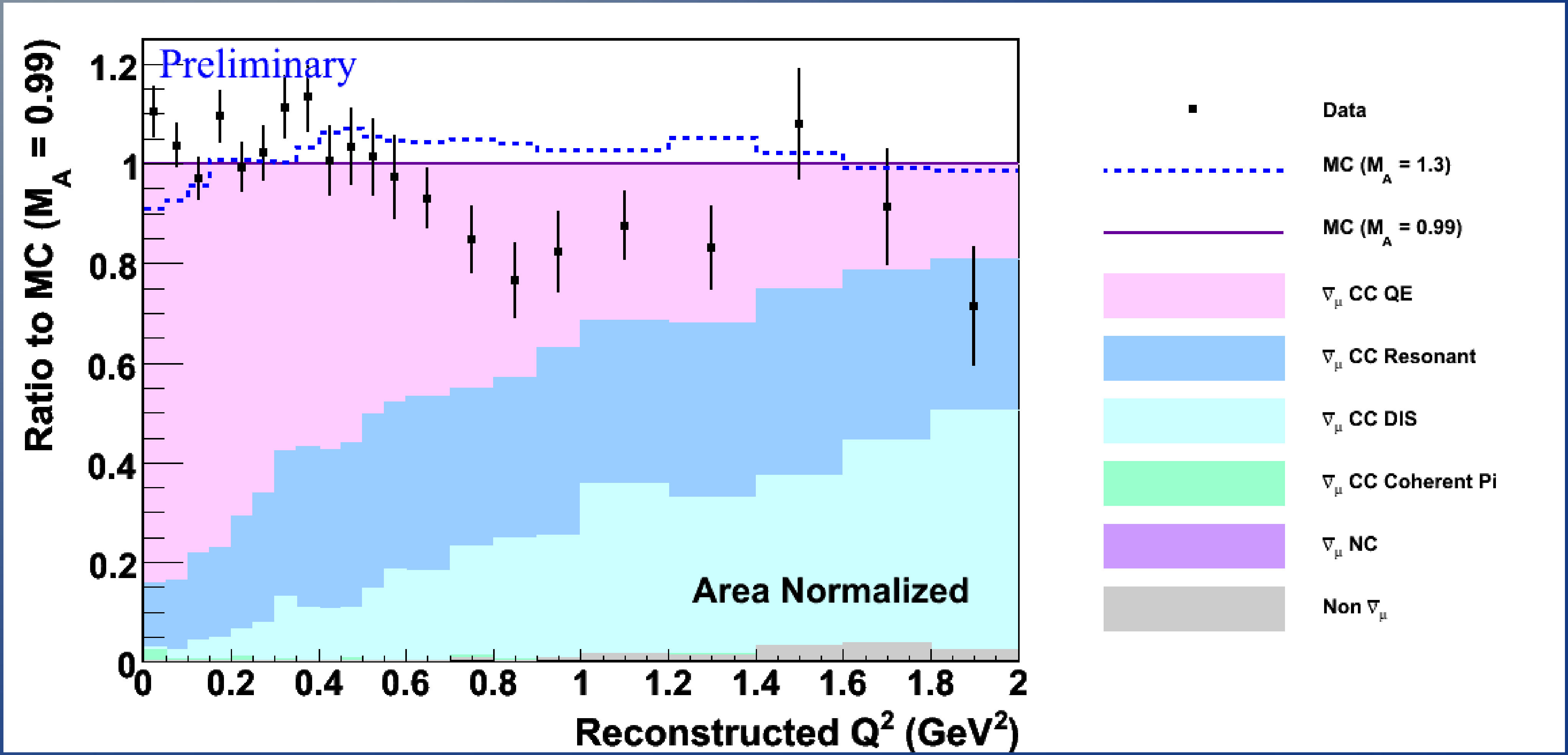


$5\ \text{GeV} < E_\nu < 10\ \text{GeV}$



Reweighted Q^2 Shape

- Reweighted Monte Carlo Q^2 distribution does not have better agreement with data



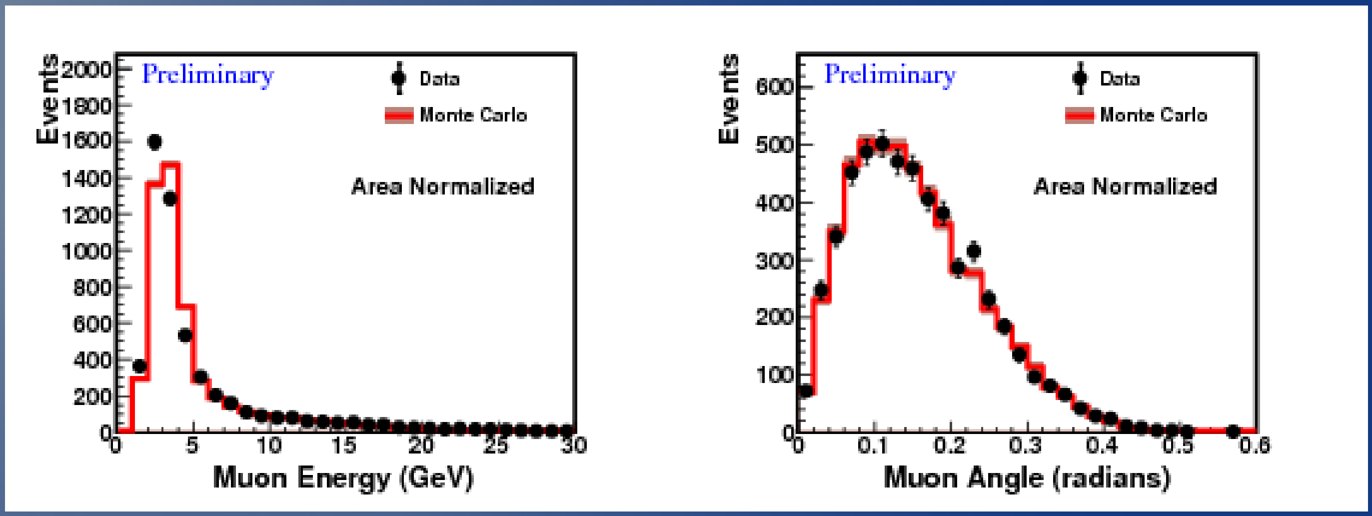
Outlook

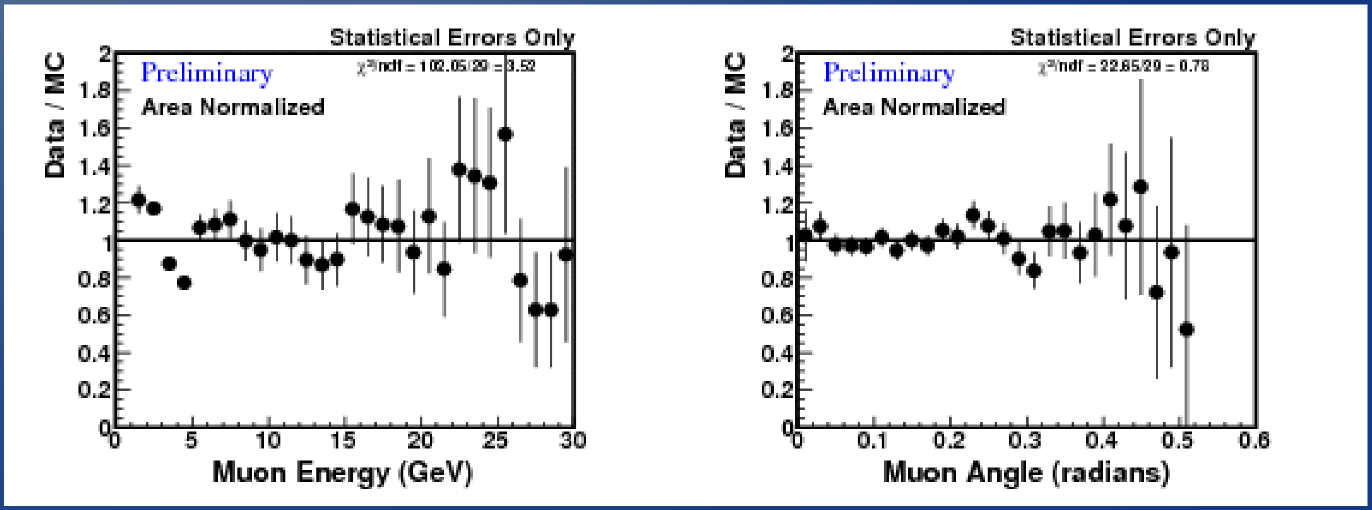
- A different value of M_A does not explain the current data/MC disagreement we observe at this stage of our analysis
- Will have distributions corrected for detector smearing soon to make more rigorous comparisons to MiniBooNE and NOMAD results
- Will incorporate additional data into the analysis
- Continuing to make strides in reconstruction and analysis techniques

Backup

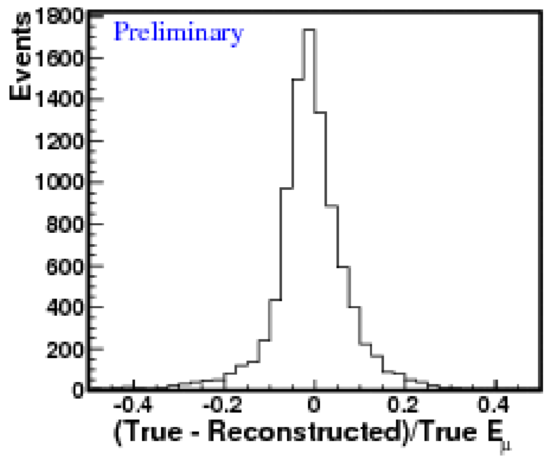
Reconstructing QE Events

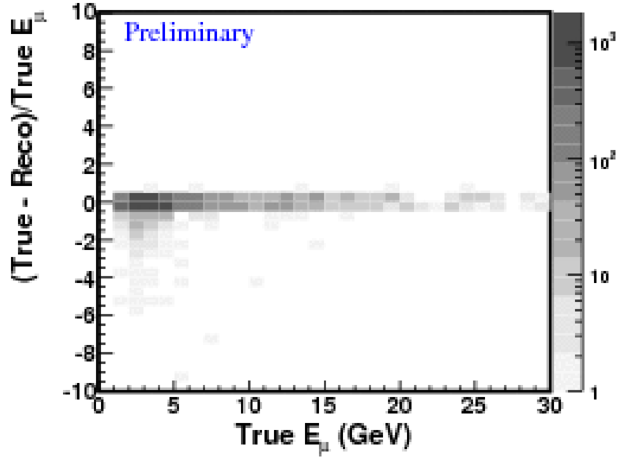
- Distributions are not corrected for smearing effects in the detector
- Good data/MC agreement for muon angle
- Discrepancy in muon energy likely comes from poor modeling of flux at NuMI focusing peak

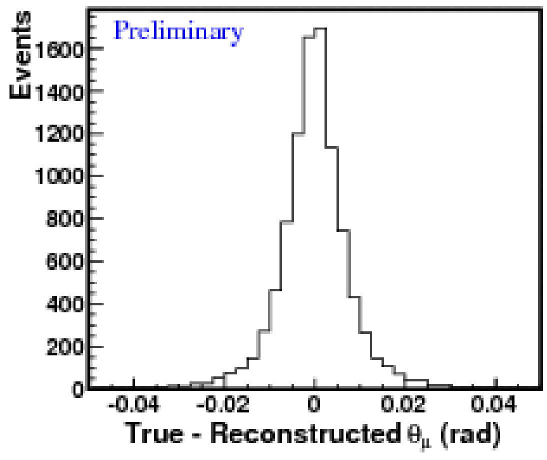


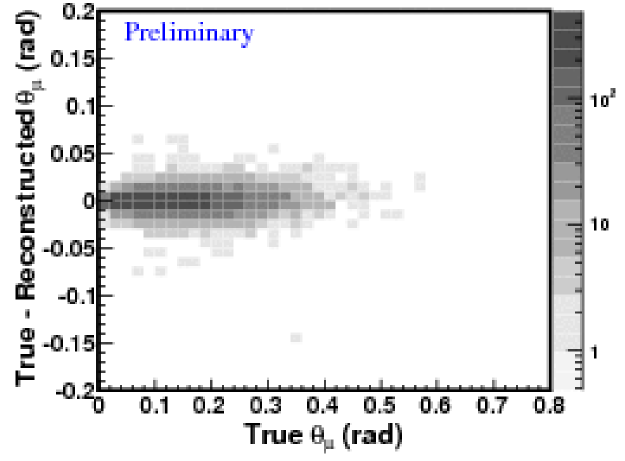


Muon Energy and Angle Resolution



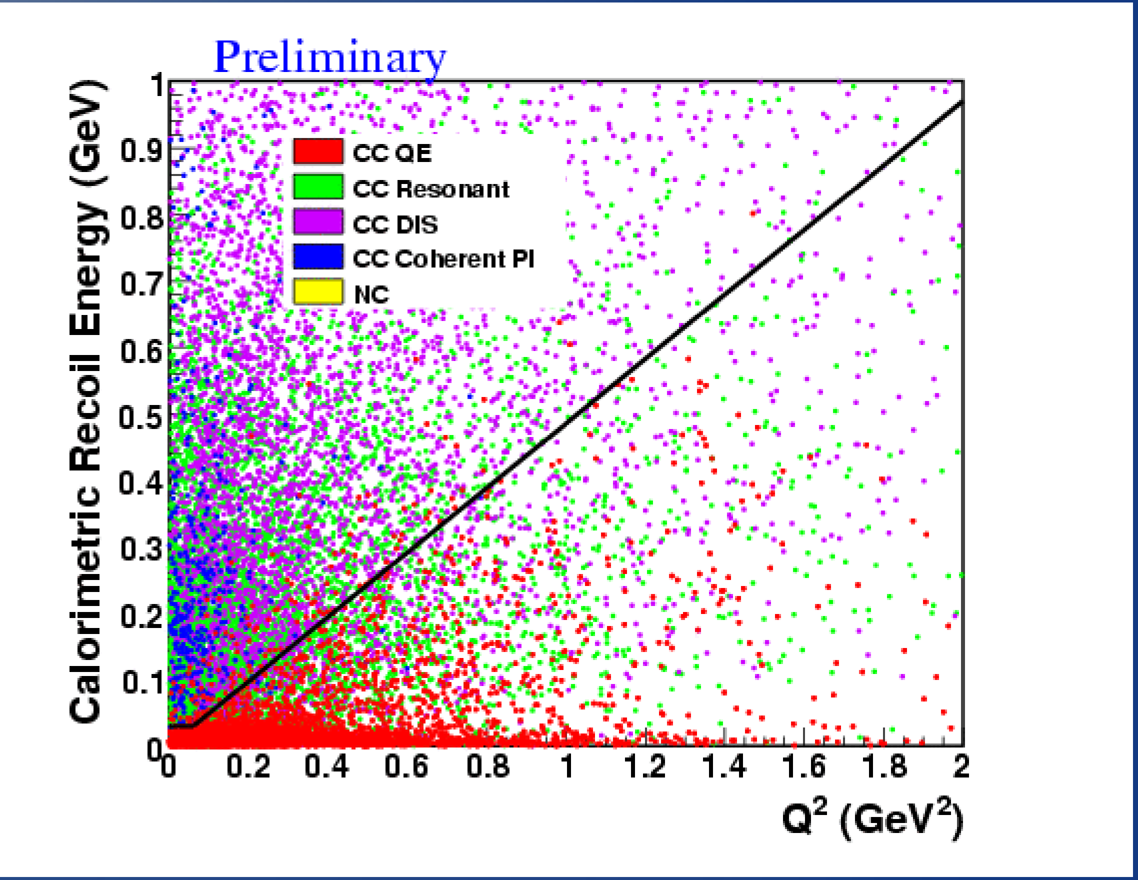






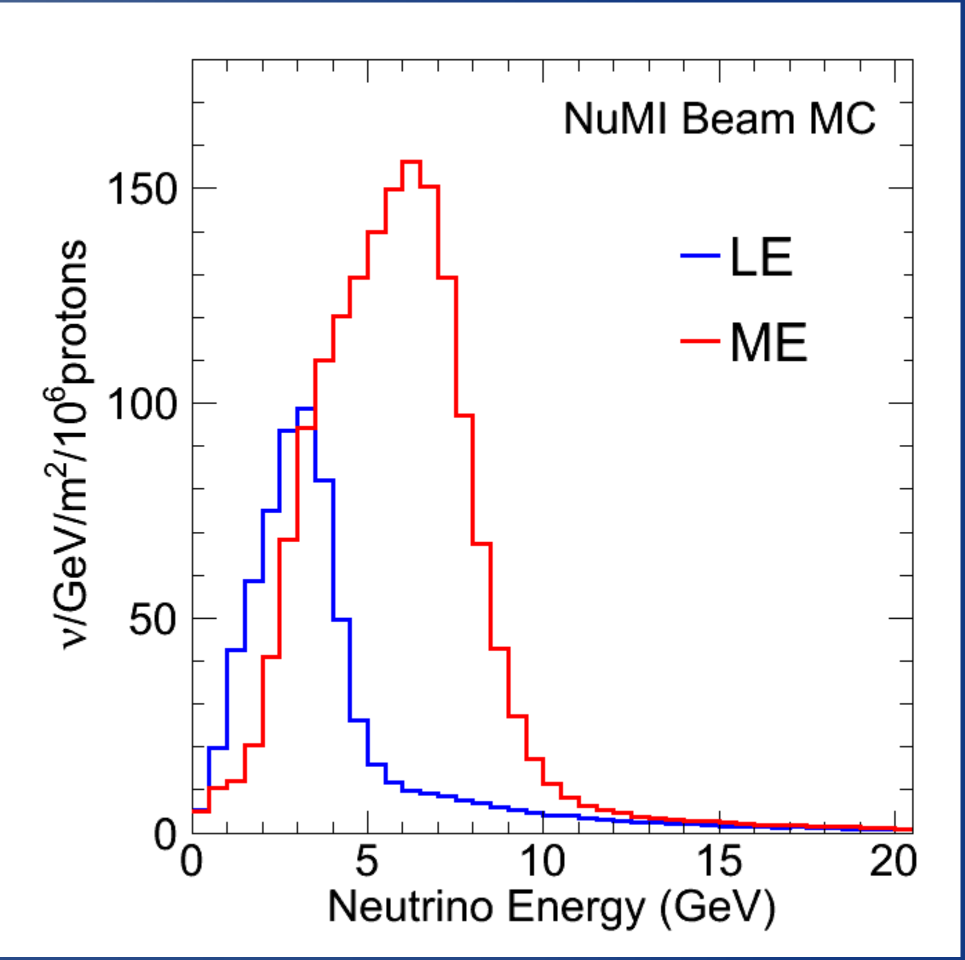
CCQE Selection Cuts

- Select tracks matched with muons in MINOS that have a vertex within our fiducial volume
- Apply a flat recoil cut of 0.03 GeV up to a value of Q^2 of 0.06 GeV^2
- Make a $Q^2/2m_p$ cut on recoil energy in the detector for Q^2 greater than 0.06 GeV^2



NuMI Beam Flux

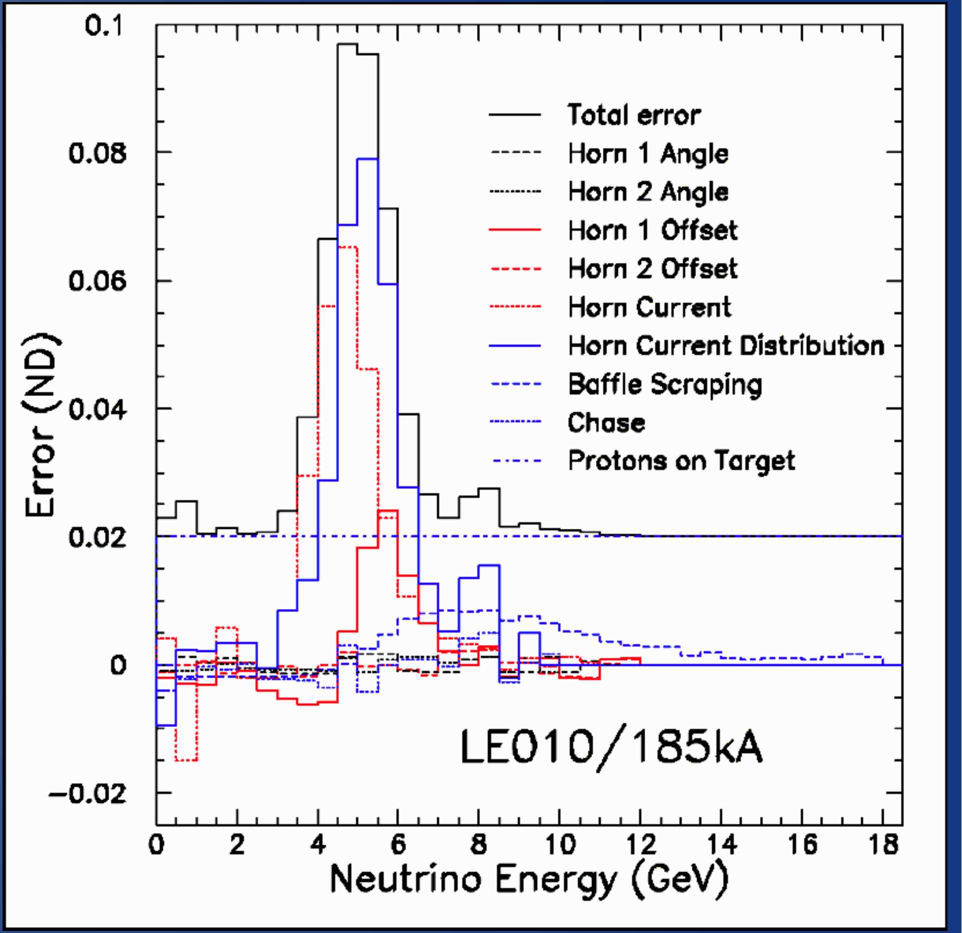
- ~35 E12 POT per spill
- Spill length/frequency = 10 μs/0.5 Hz
- Beam power: 300-350 kW
- Goal – 7% shape error, 10% normalization error



NuMI Beam Flux

Three strategies:

- Vary horn current and distance of target from horns, study how event rates change
- Measure muons from pion/kaon decays with muon monitors to predict pion/kaon production off the target
- Use world hadron production data to predict pion and kaon production



GENIE Generator Details

For QE Generation, specific details of model are:

- General equation is Llewellwyn-Smith (with lepton mass terms)
- The pseudo-scalar form factor is taken from PCAC
- Eletromagnetic 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