Study of Quasi-Elastic Scattering in the NOvA Detector Prototype

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For the NOvA Collaboration

New Perspectives 2013 conference
June 11, 2013

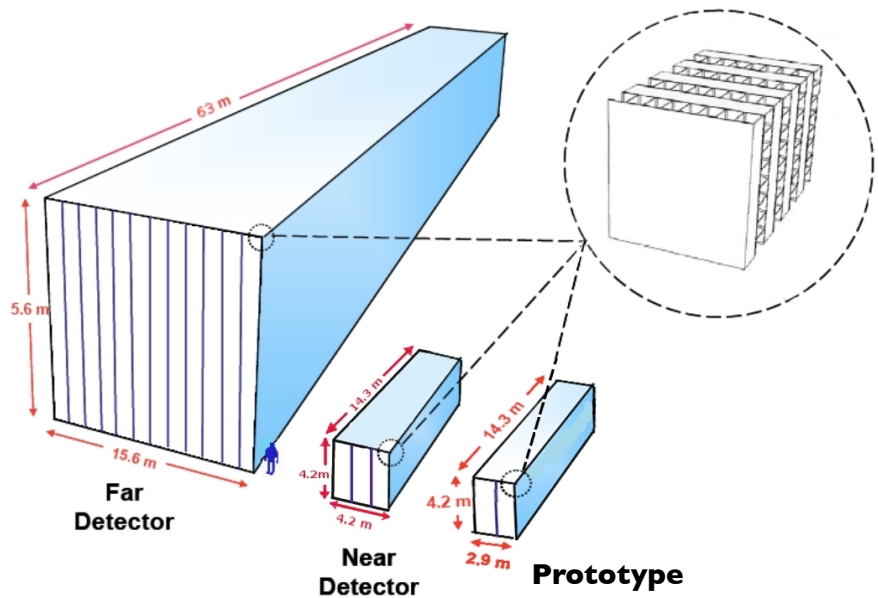
Outline

- Brief overview of the NOvA experiment
- Neutrino production and detector components
- Study of Quasi-Elastic scattering in the NOvA Detector Prototype

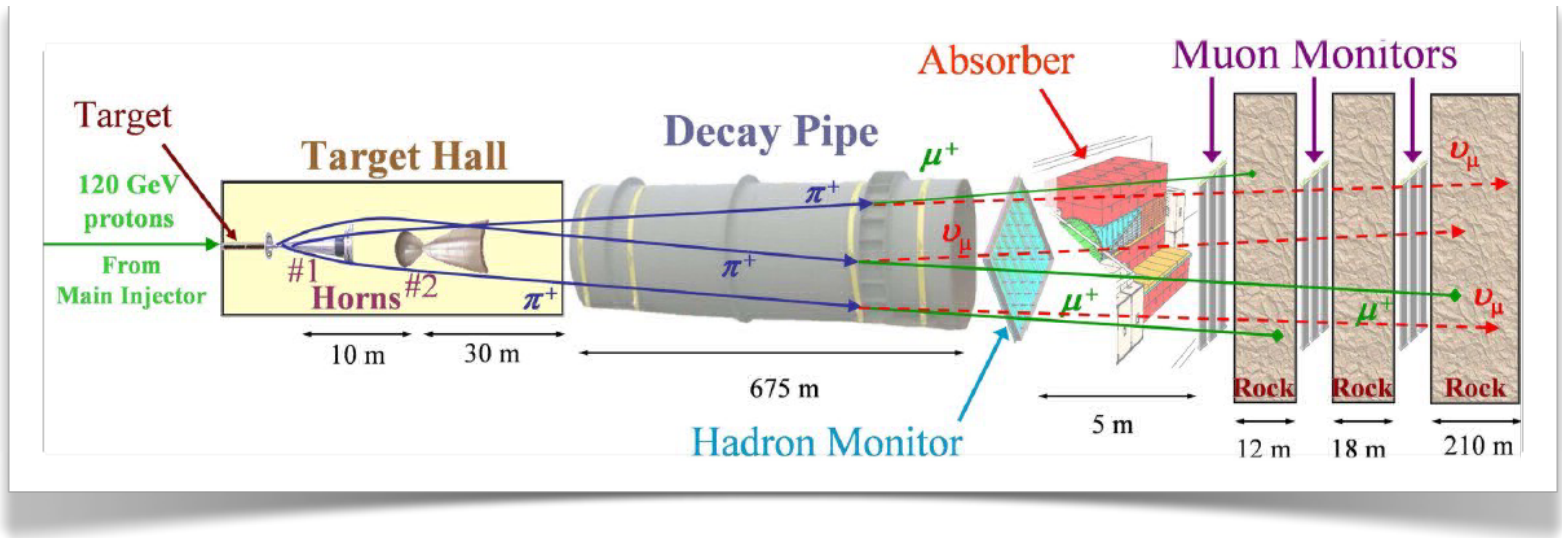
Physics Goals for NOvA

NOvA: NuMI Off-axis νe Appearance Experiment

- NOvA will study ν_e appearance in ν_μ and $\bar{\nu}_\mu$ beam
- Measure the θ_{13} and search for the mass ordering
- Search for the CP violation phase δ
- Precise measurement of θ_{23} and Δm^2_{32}
- Cross section measurements

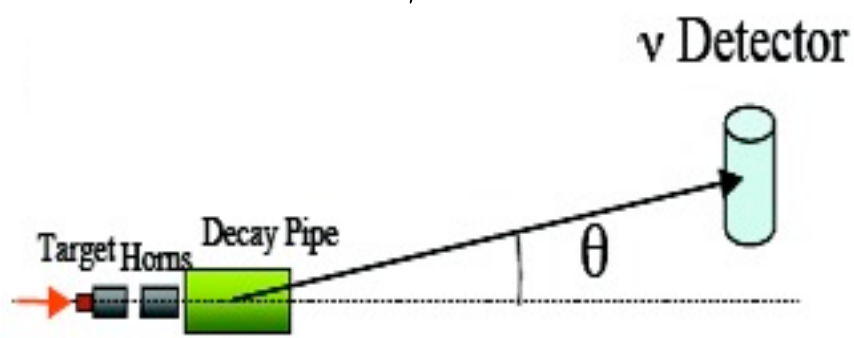


Neutrino Production

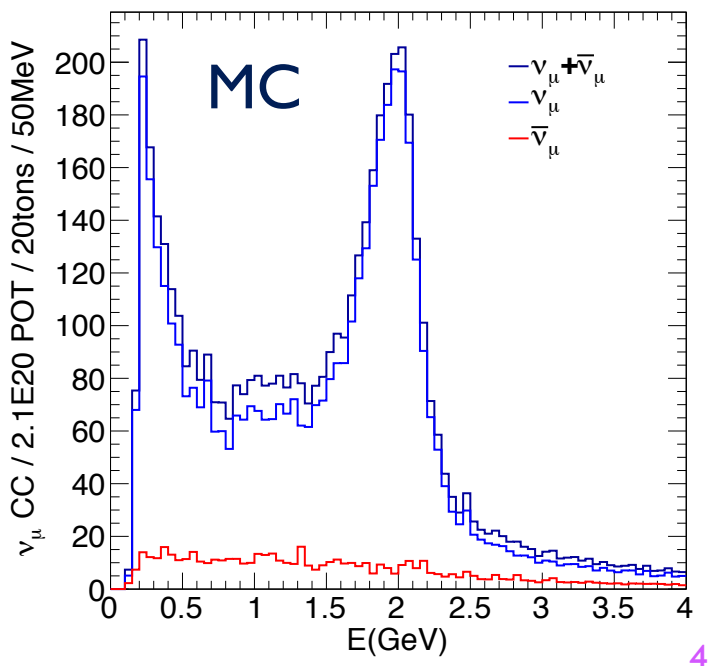


- Detector Prototype 110 mrad off-axis

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

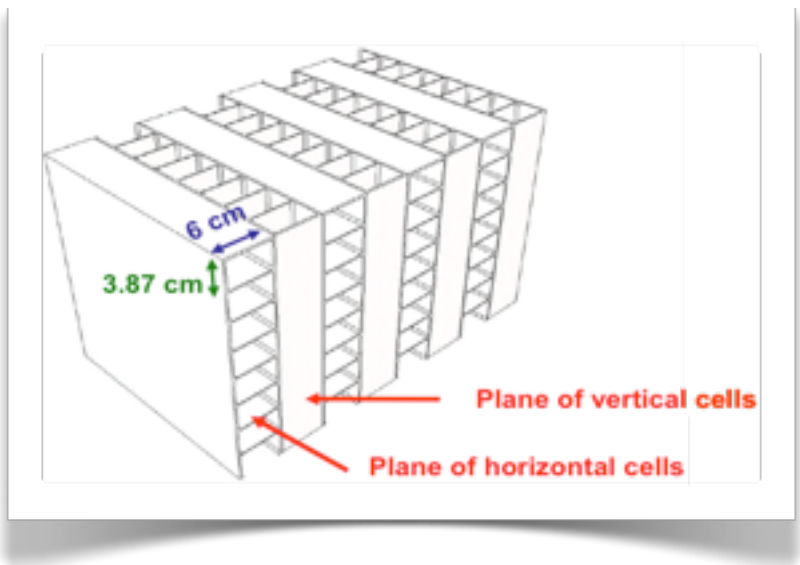


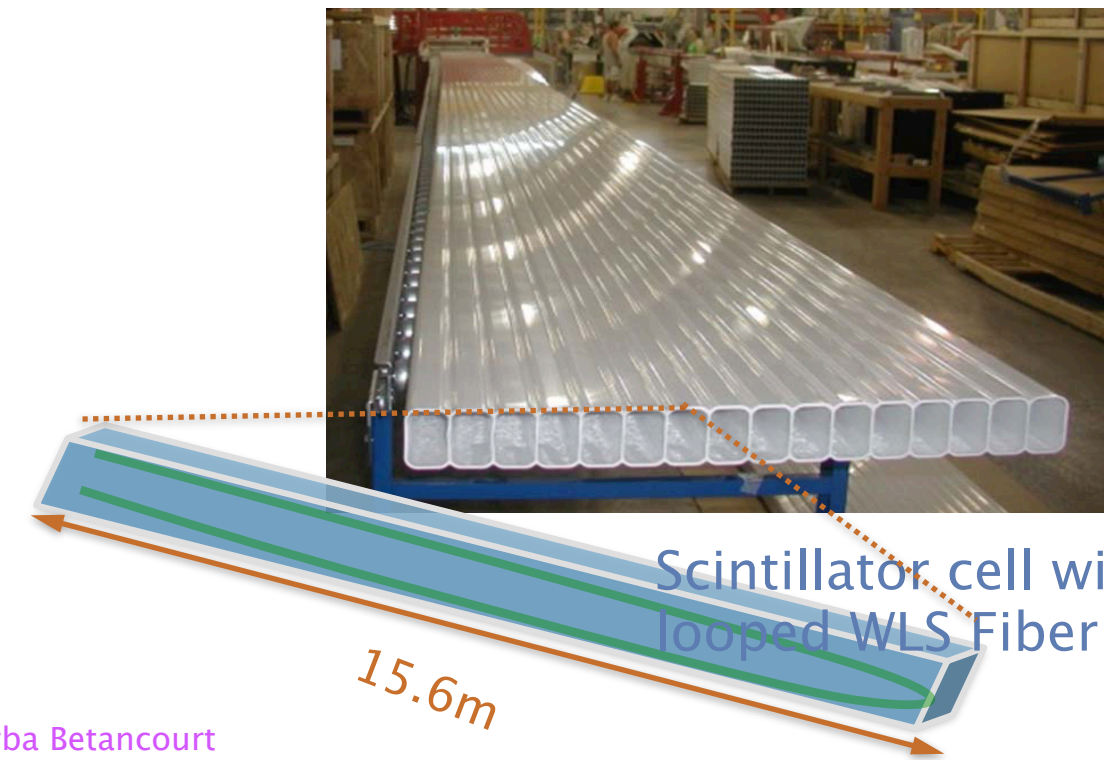
Detector Prototype energy spectrum



Detector Components

- Extrusion modules are made from 32 cells
- Single sided readout from 0.7 mm diameter looped WLS fiber
- Cells filled with mineral oil and liquid scintillator
- Avalanche of Photodiodes (APD) converts light to an electrical signal, actively cooled to -15C

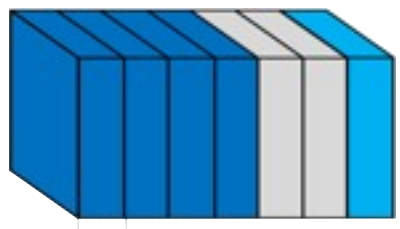




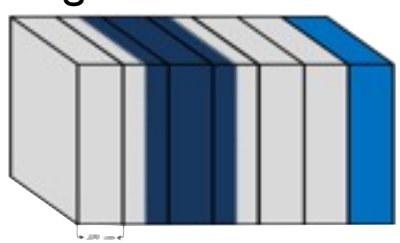
Detector Prototype

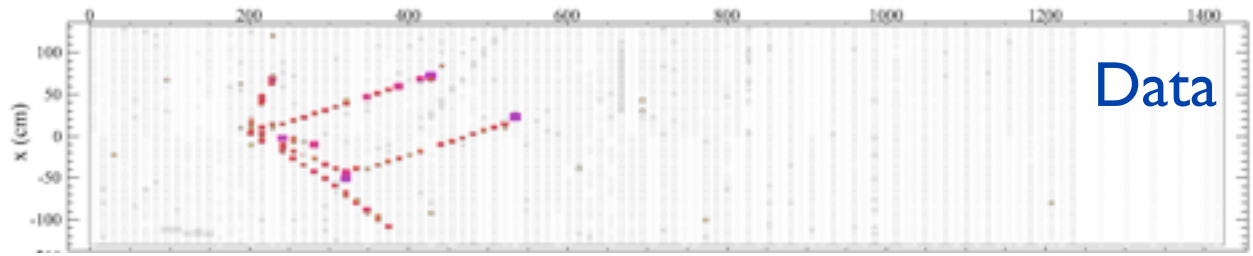
- Detector located on the surface at Fermilab
- Prototype Detector used to test all detector systems: assembly technique, DAQ, APD installation, scintillator filling, electronic installation, calibration

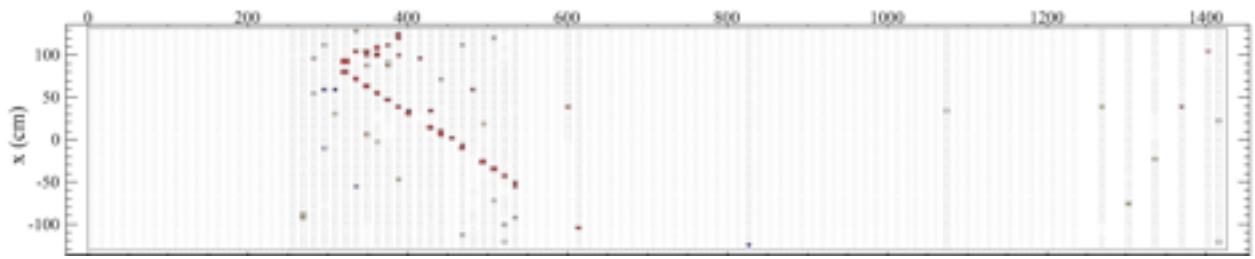
Config 1



Config 2







Fully instrumented
Mostly instrumented
Partially instrumented
Uninstrumented

Proton On Target (POT) collected:
Configuration 1: 9.6e+18
Configuration 2: 1.7e+20

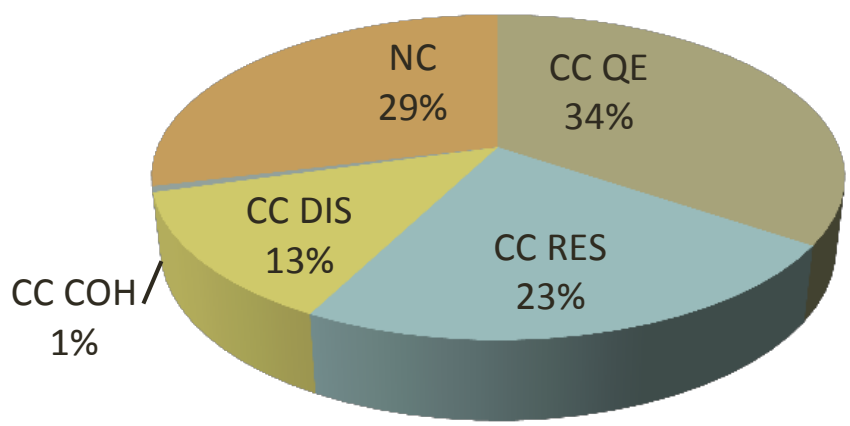
Commissioning Operations

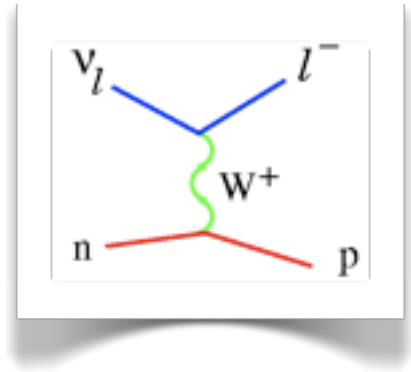
APD tests helped:

- Developed surface coating for APDs to protect the surface from potential contact with contaminants
- Added an active air drying system to keep out condensation due to cooling

Quasi-Elastic Studies

- Developed a selection criteria to identify the QE interactions and reject background
  - Background for the QE interactions:
    - Cosmic muons
    - Resonance (RES), Deep Inelastic (DIS), Neutral Current (NC), Coherent (COH) interactions

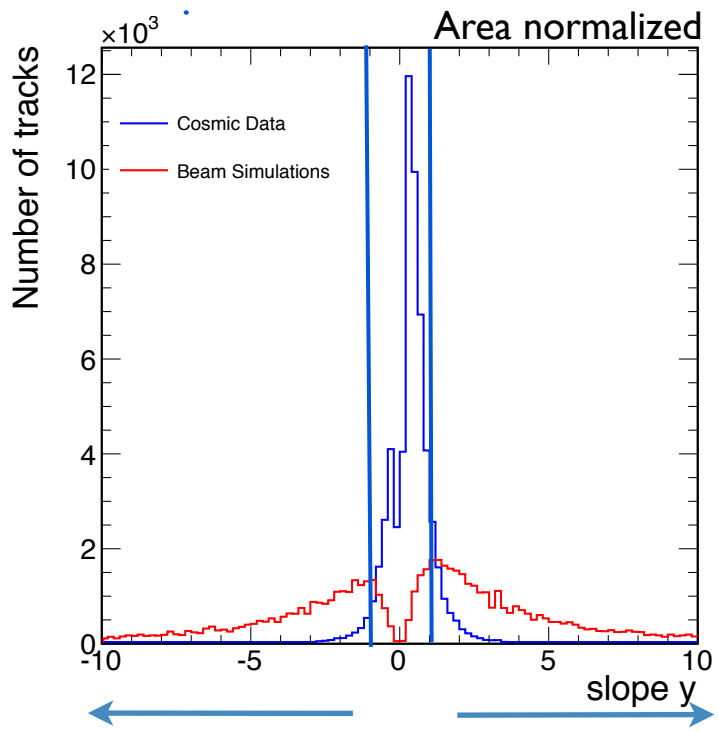




Cosmic Background

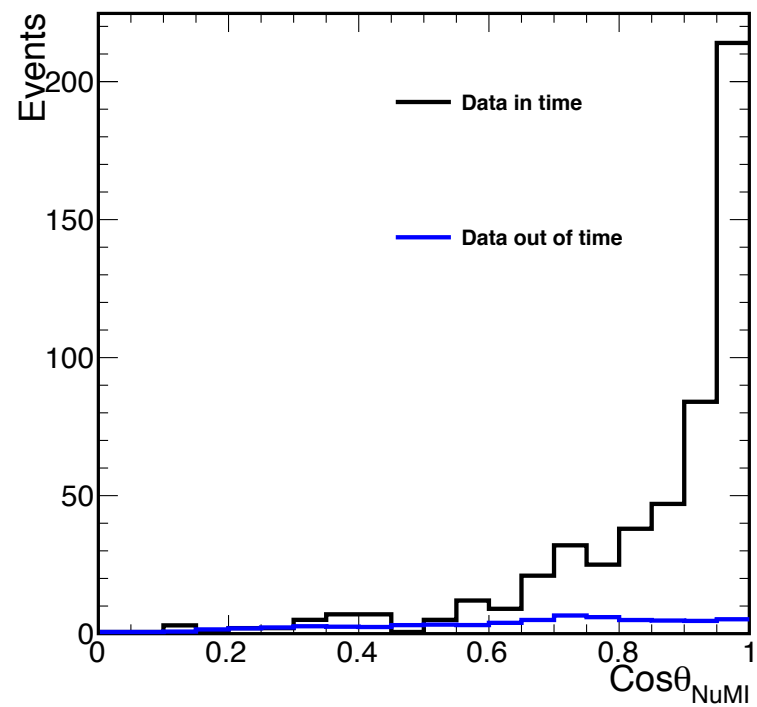
- Cosmic muons:
  - We use a selection to reject the cosmic background: timing cut and the inverse of slope of the tracks in the vertical view

Inverse of slope of the tracks in the vertical



$$slope = \frac{Z2 - Z1}{Y2 - Y1}$$

Reconstructed particle tracks angle with respect to the beam direction



We use the data out of time to estimate the cosmic background

Quasi-Elastic Selection

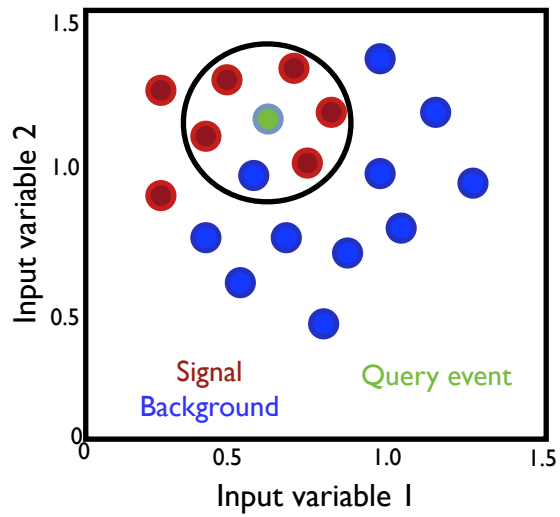
- Using a k Nearest Neighbors Algorithm (kNN) to select muons from QE interactions, where k is the number of neighbors
- Nearest Neighbors Algorithm searches for k events that are closest to a query event using the Euclidean distance

$$R = \left(\sum_{i=1}^{n_{var}} |x_i - y_i|^2\right)^{\frac{1}{2}}$$

- Estimates a multidimensional probability density function by counting the number of signal and background events in a small neighborhood around the query event

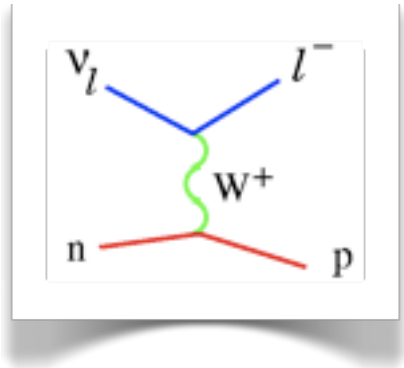
$$\mathrm{kNN_{ID}} = \frac{k_S}{k_S + k_B}$$

where k_S and k_B are the number of signal events and the number of background events



Quasi-Elastic Selection

- Preselection cuts:
  - Event within 10 microsecond beam spill
  - Interaction point 50cm from the edge of the detector
  - One and only one reconstructed track
  - The slope of the tracks is not near vertical (cosmic rejection)
  - Track does not exit the detector



- Quasi-Elastic interaction identification using a k Nearest Neighbors (kNN) algorithm

  Studies in MC use channel masks for a partially instrumented detector

Quasi-Elastic Selection

- Preselection cuts:
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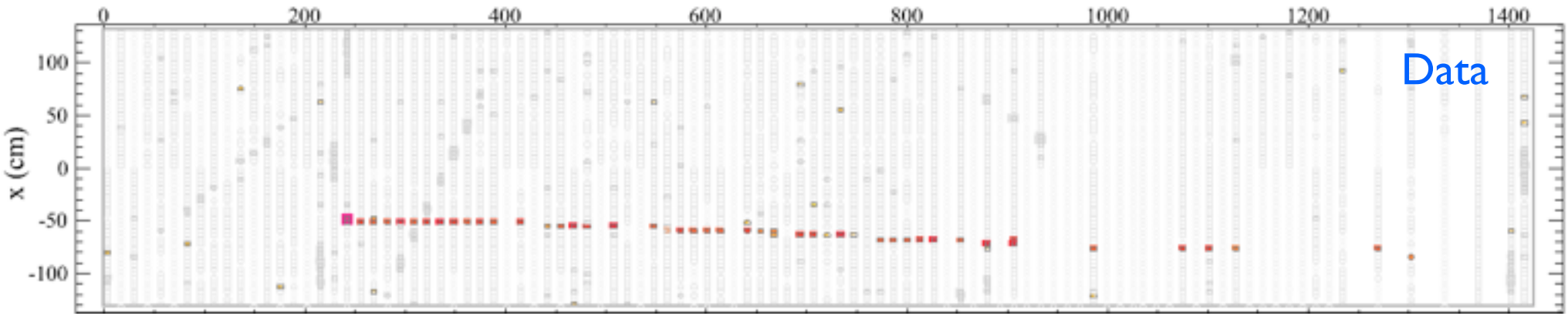
- Quasi-elastic interaction identification using a k Nearest Neighbors (kNN) algorithm

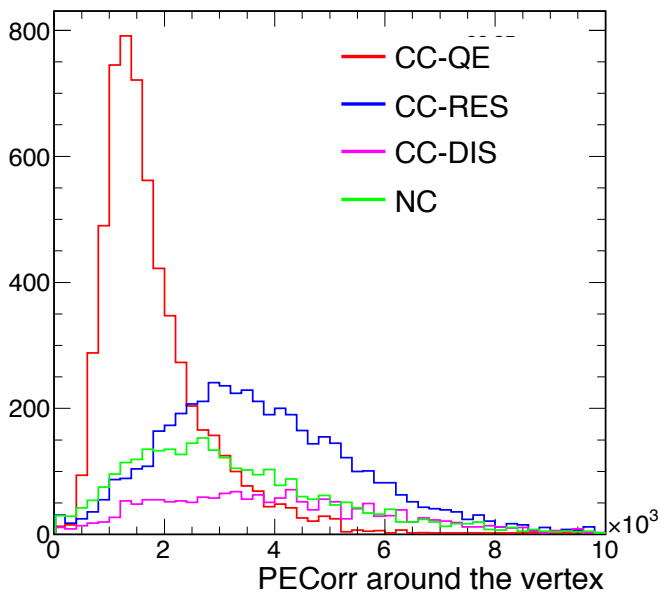


Three Input Variables

Simulations

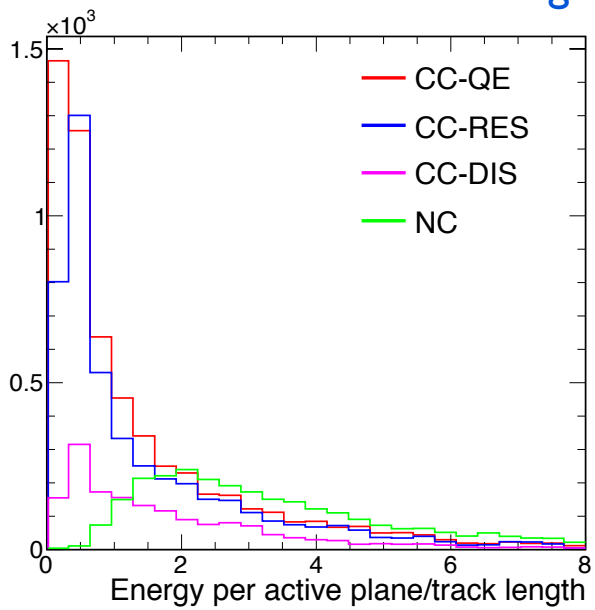
- Using a k Nearest Neighbor (kNN) algorithm with three input quantities

Energy around the vertex



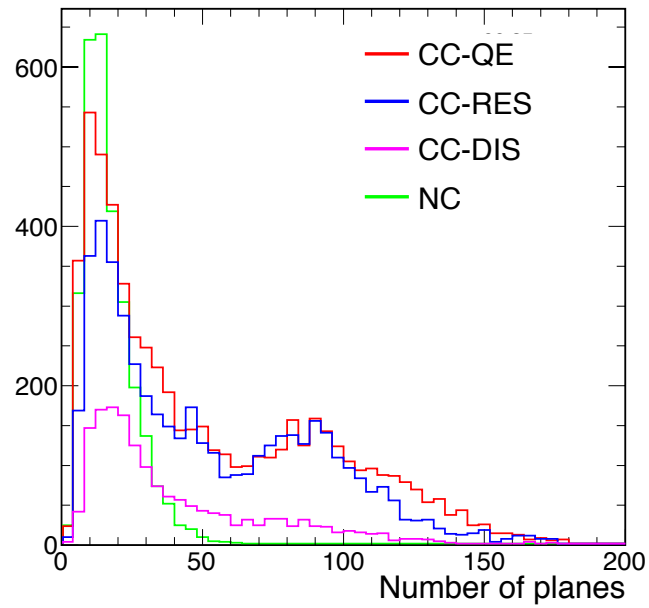
RES, DIS and NC deposit more energy around the vertex

Mean energy per active plane normalized to track length



NC interactions deposit more energy per plane

Number of planes

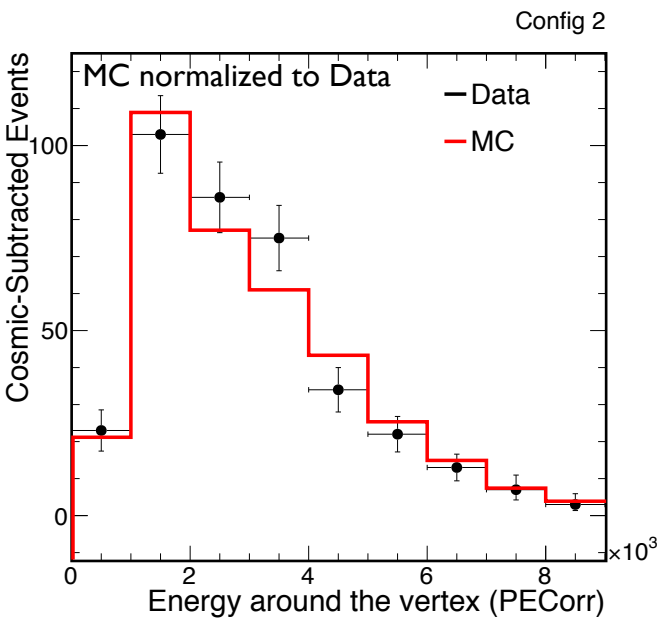


Pions from NC interactions travel shorter distances than CC

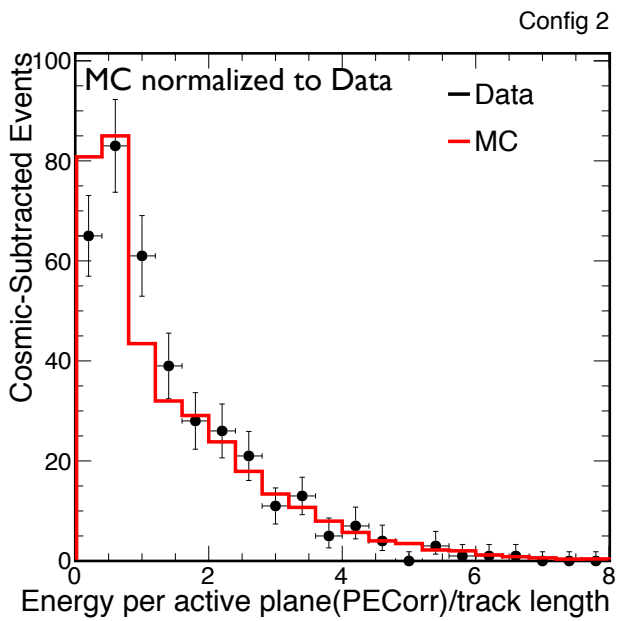
Three Input Variables

- Using a k Nearest Neighbors (kNN) algorithm with three input quantities

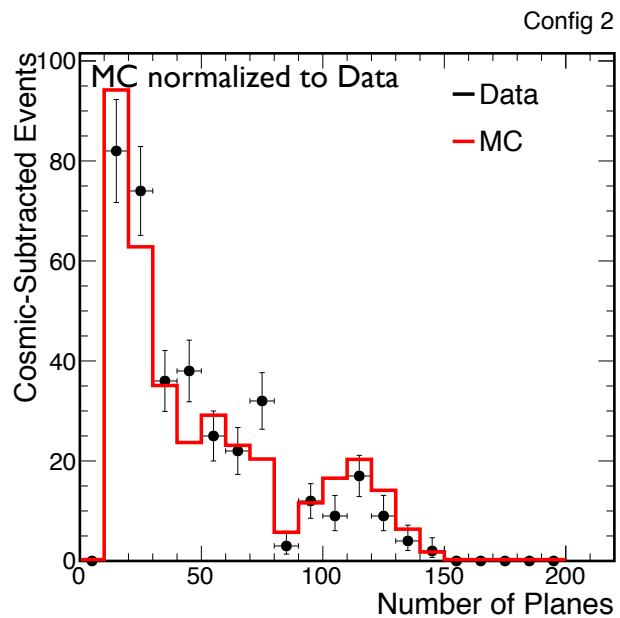
Energy around the vertex



Mean energy per active plane normalized to track length



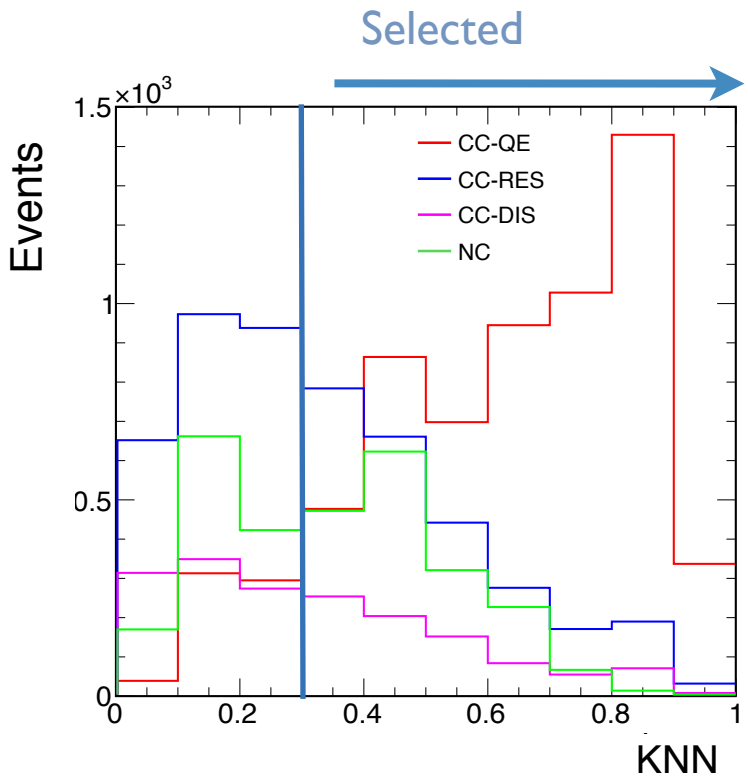
Number of planes

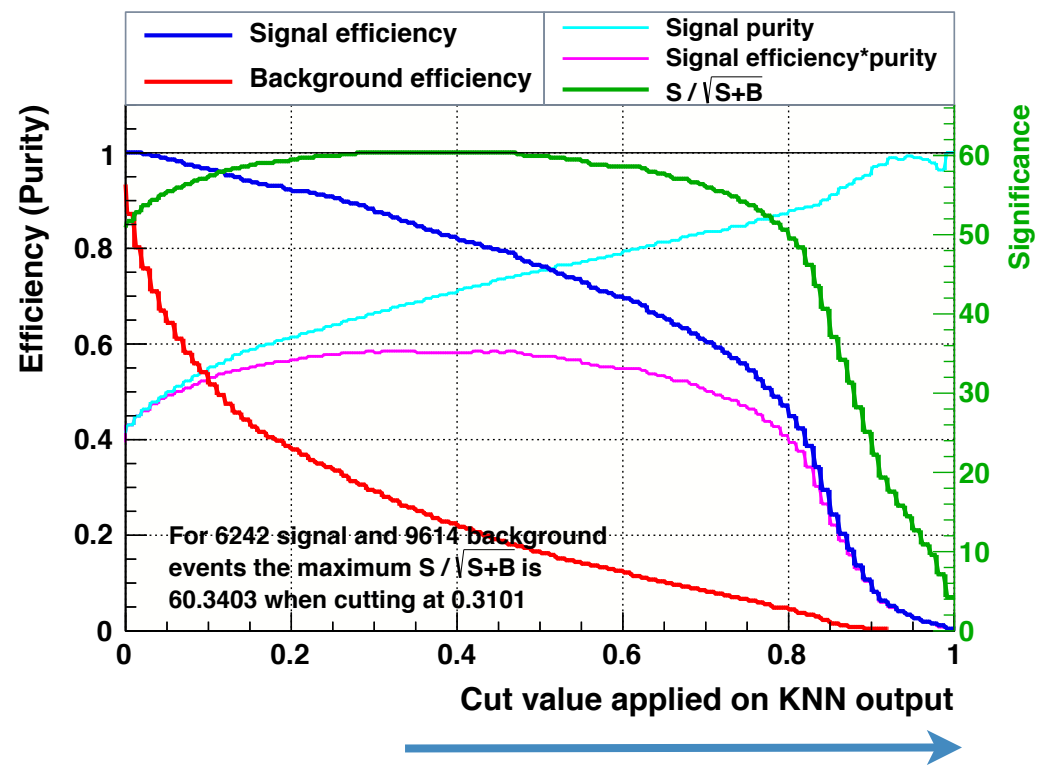


Beam candidates after cosmic background subtraction and Monte Carlo simulation for preselected events

Quasi-Elastic Separation

- After training the kNN with the input variables on MC samples QE, RES, DIS and NC events apply it to a different MC sample





- kNN selection:

For kNN>0.3, events have 65% purity and 85% efficiency for the partially instrumented detector for both configurations

Quasi-Elastic Separation

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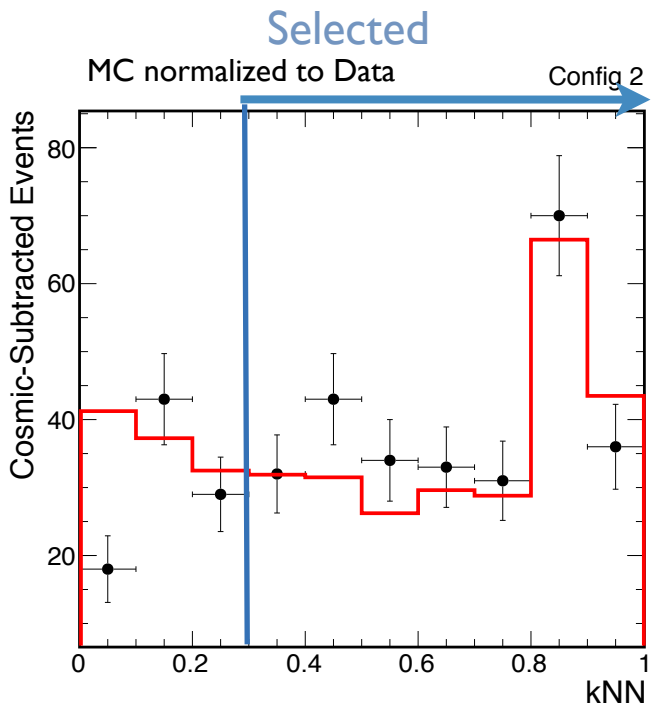
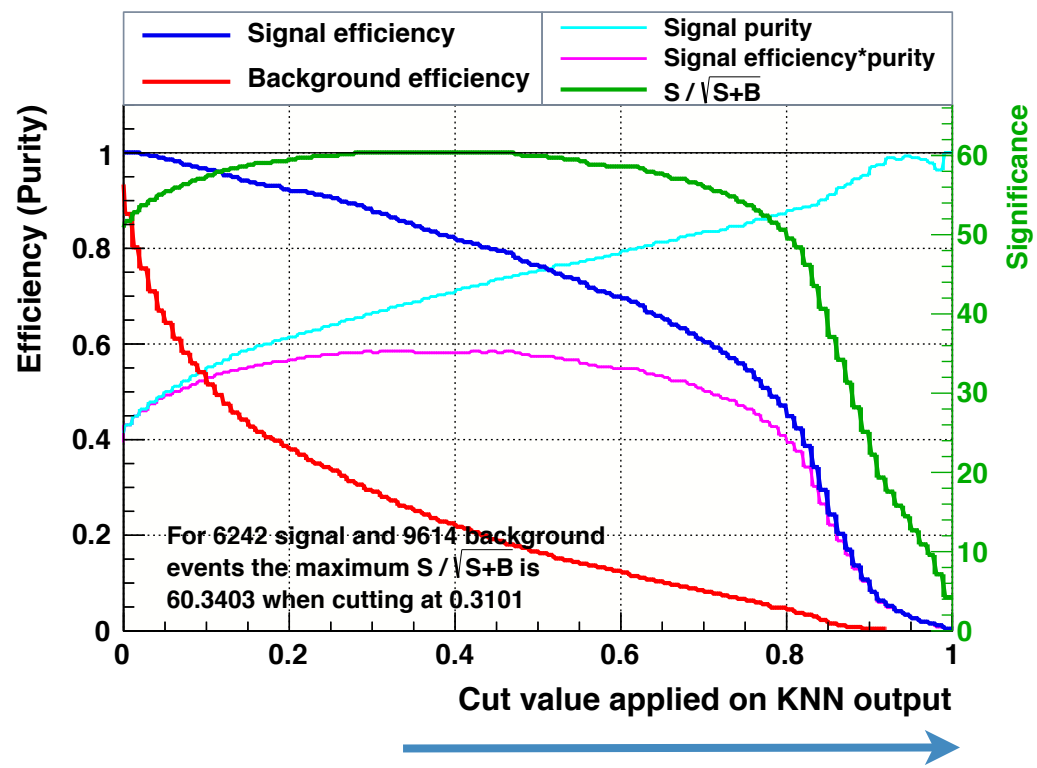




- kNN selection:

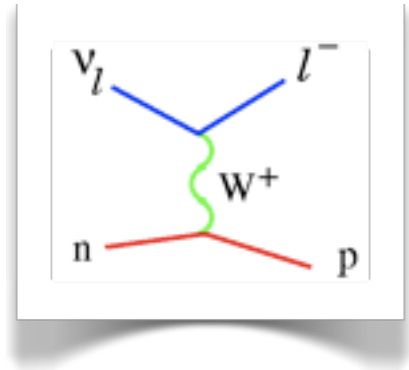
For kNN>0.3, events have 65% purity and 85% efficiency for the partially instrumented detector for both configurations

Neutrino Energy and Q^2 Reconstruction

- Neutrino energy is reconstructed from the length of the track and its angle from the beam direction

$$E_\nu = \frac{2(M_n^{'})E_\mu - ((M_n^{'})^2 + m_\mu^2 - M_p^2)}{2[(M_n^{'}) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}$$

$$M^{'} = M_n - E_B \quad and \quad E_B = 25MeV$$



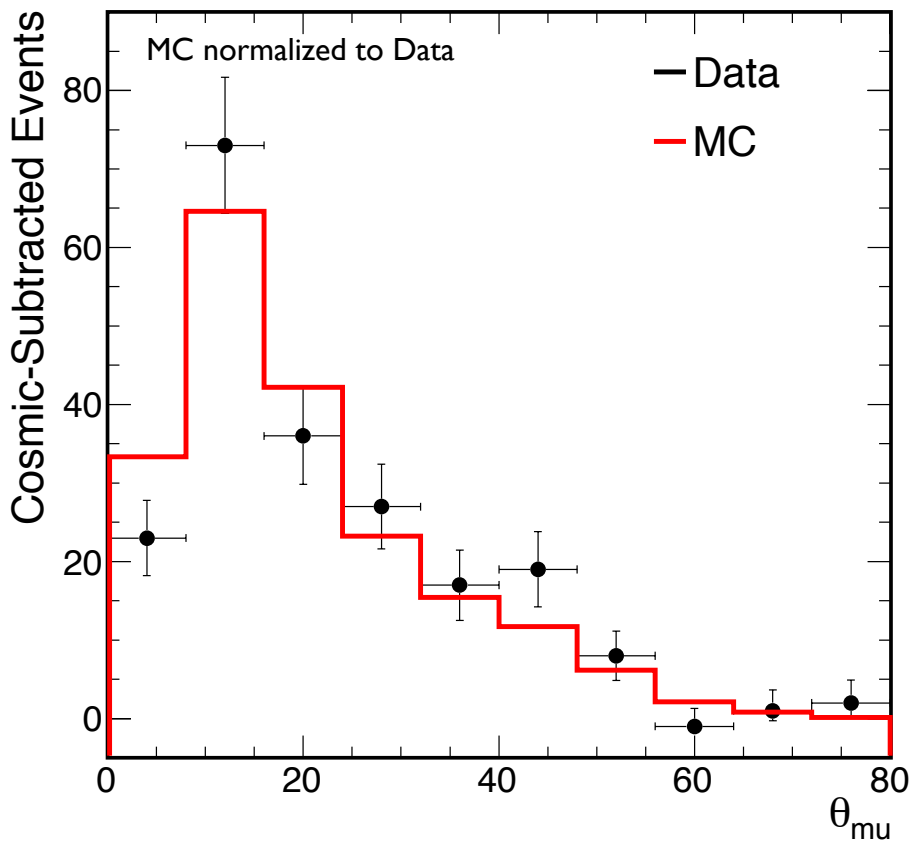
- Four momentum is reconstructed using

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}cos\theta_\mu)$$

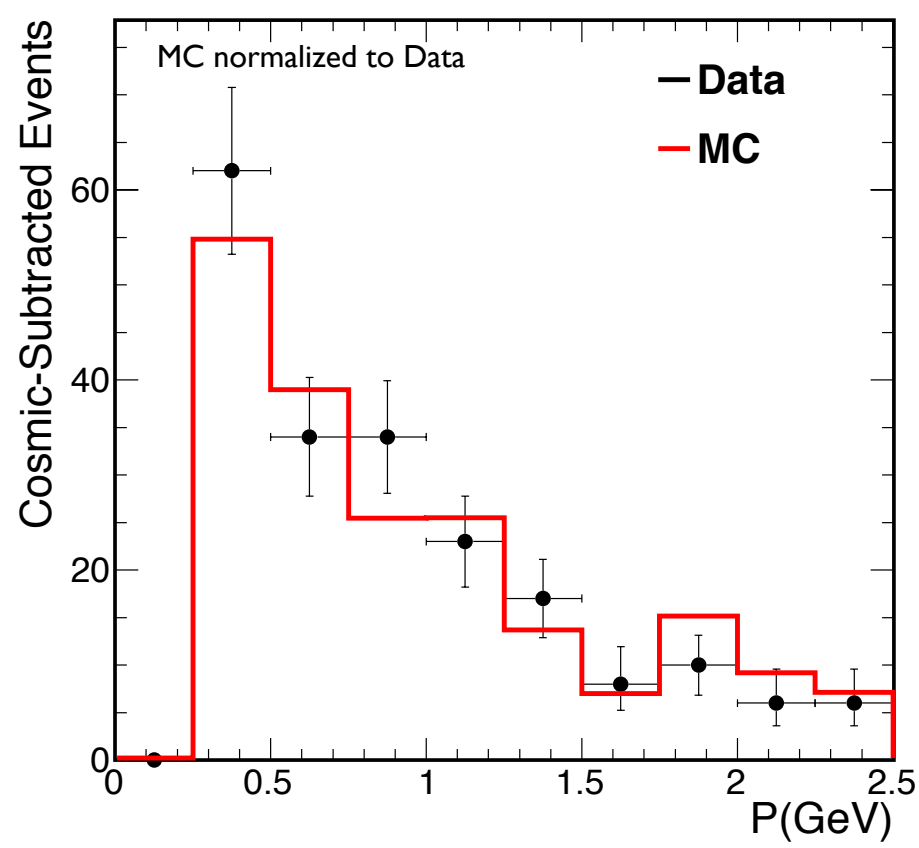
Angle and Momentum

- Momentum is obtained from the range of the tracks

Angle



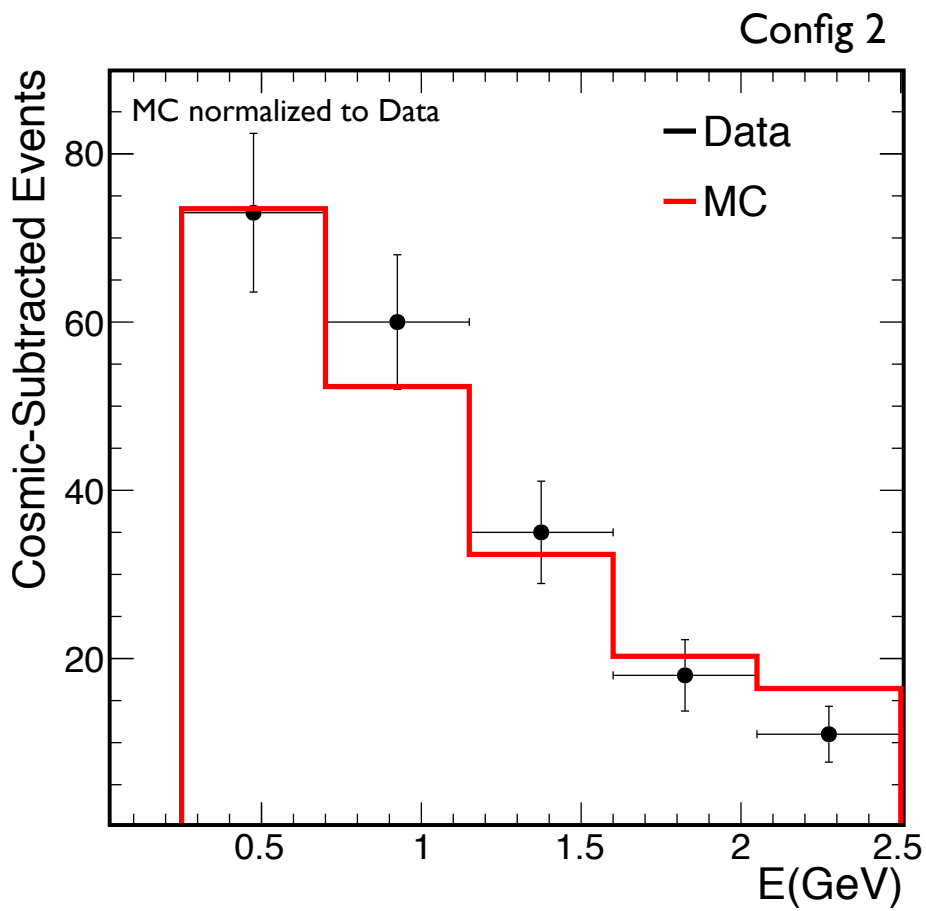
Momentum



Angle and momentum for ν_μ CC QE selected events after cosmic background subtraction

Neutrino Energy

- Reconstructed neutrino energy



$$E_\nu = \frac{2(M')E_\mu - ((M')^2 + m_\mu^2 - M_p^2)}{2[(M') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}$$

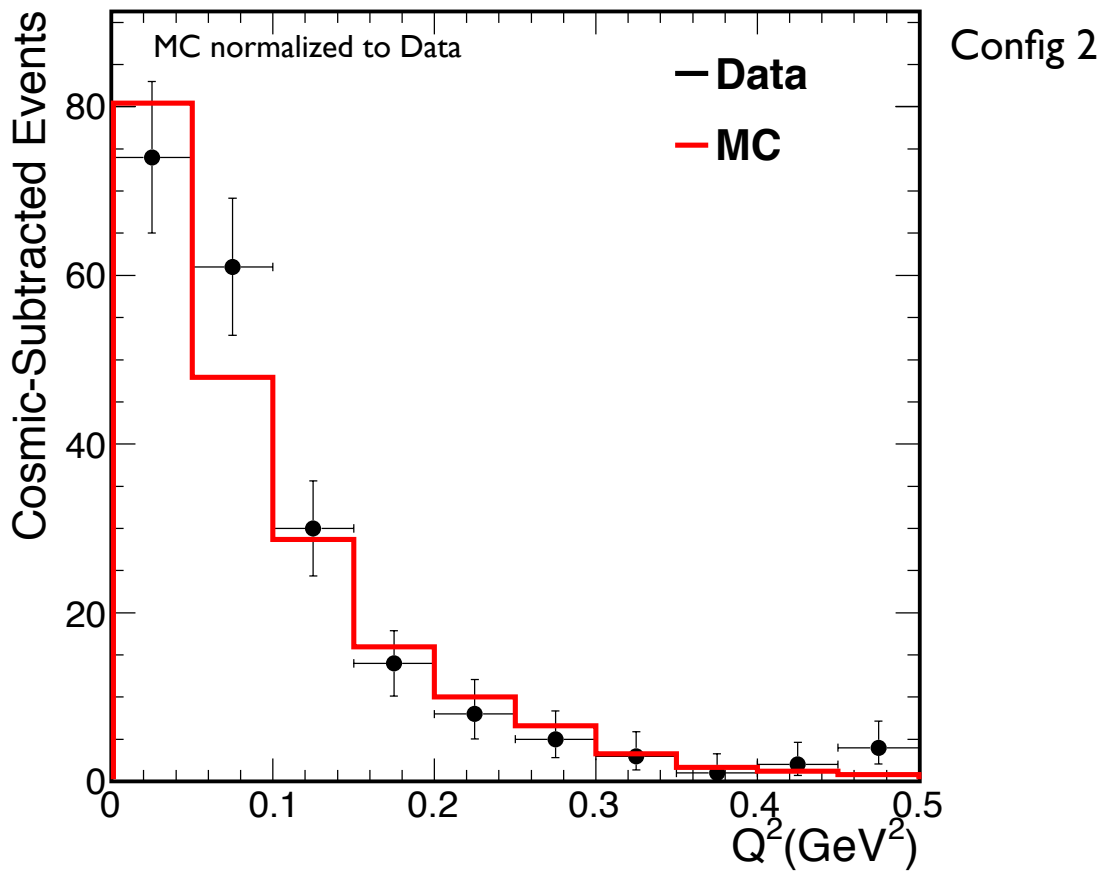
$$M' = M_n - E_B \quad and \quad E_B = 25MeV$$

Neutrino Energy for ν_μ CC QE selected events after cosmic background subtraction

Four Momentum Transfer

- Reconstructed four momentum transfer

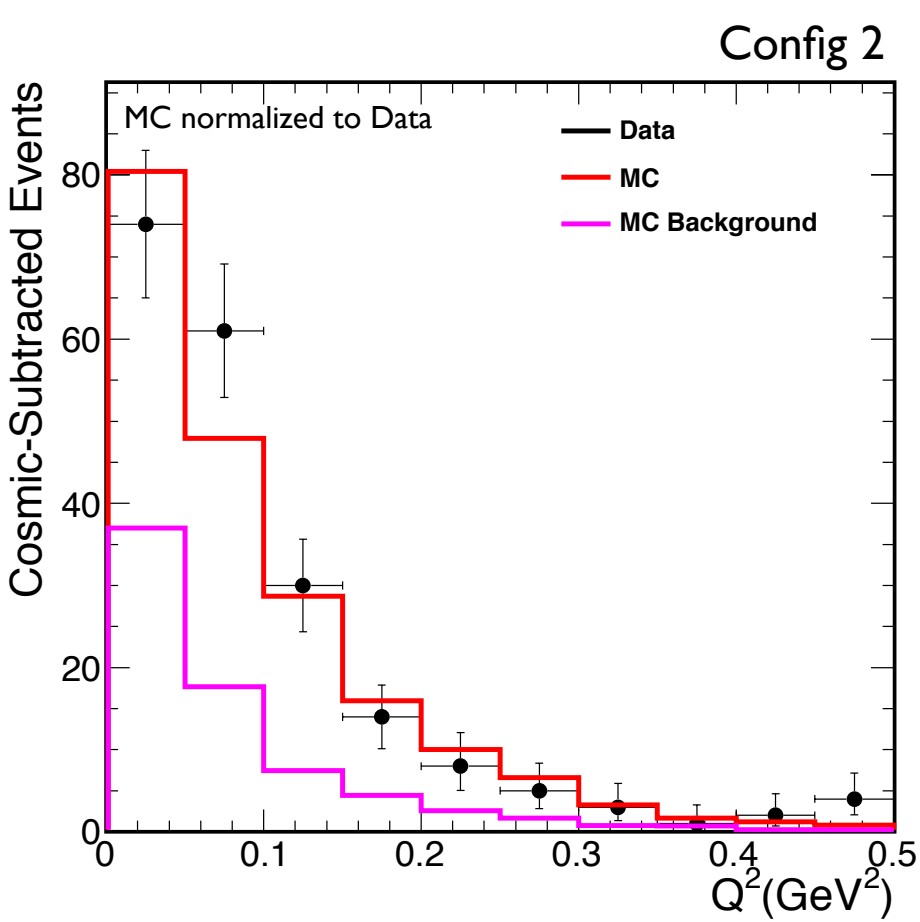
$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}cos\theta_\mu)$$

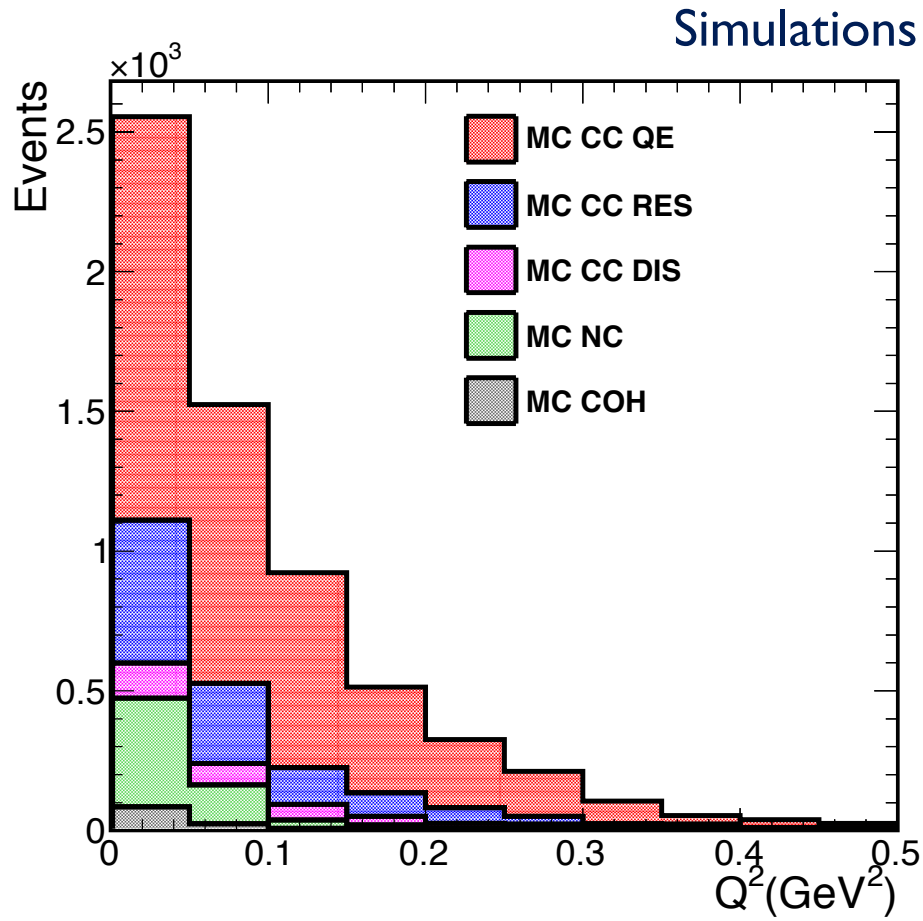


Four momentum transfer for ν_μ CC QE selected events after cosmic background subtraction

Four Momentum Transfer

- Selected CC QE four momentum transfer

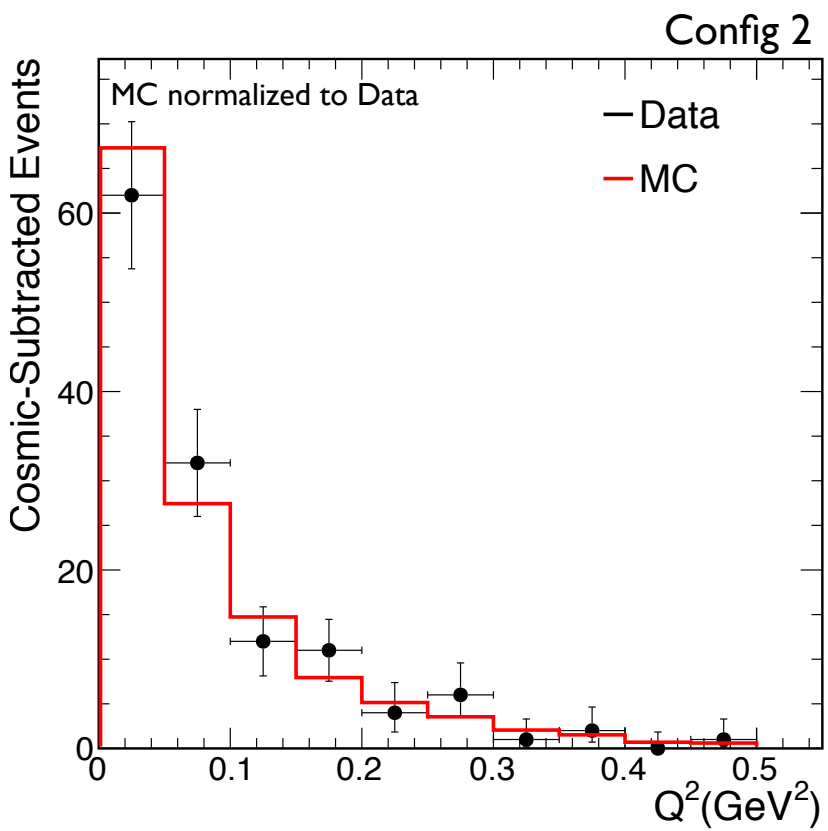


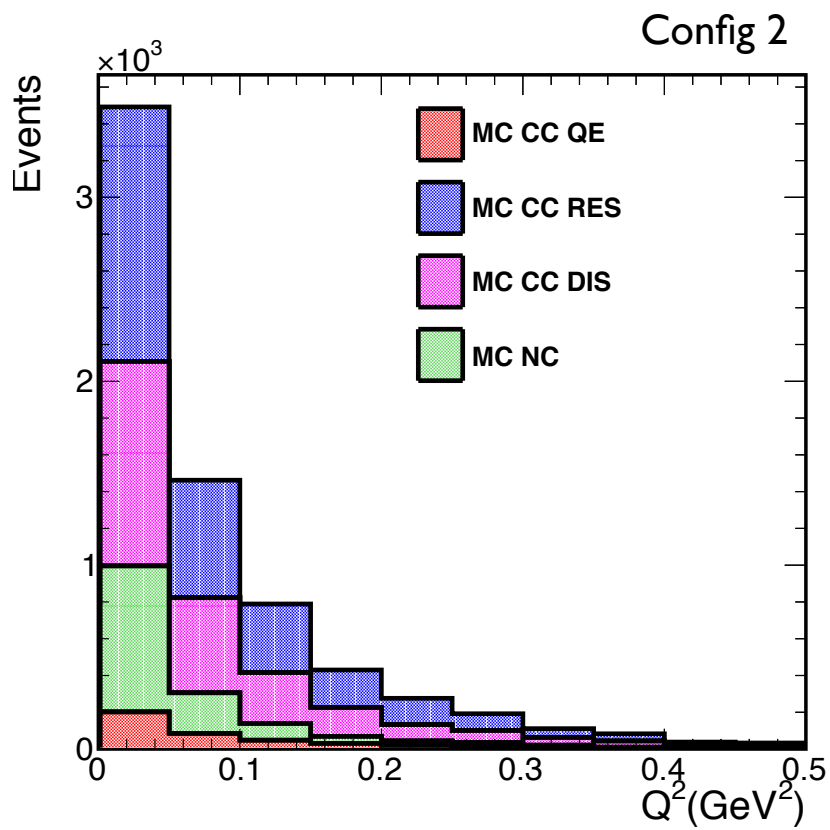


For ν_μ CC QE selected events after cosmic background subtraction and MC simulation

Background Study

- Background dominated data with two reconstructed tracks from the interaction is used to cross check the Monte Carlo for background events
- Each track has a minimum of four hits in each view
- Longest track used to determine the energy and four momentum transfer





- Background data agrees with MC simulations

Single Differential Cross Section

- Single differential cross section

$$\frac{d\sigma}{dQ^2} = \frac{\sum_j M_{ij} N_{iQE}}{\Delta Q^2 \epsilon_i \phi T}$$

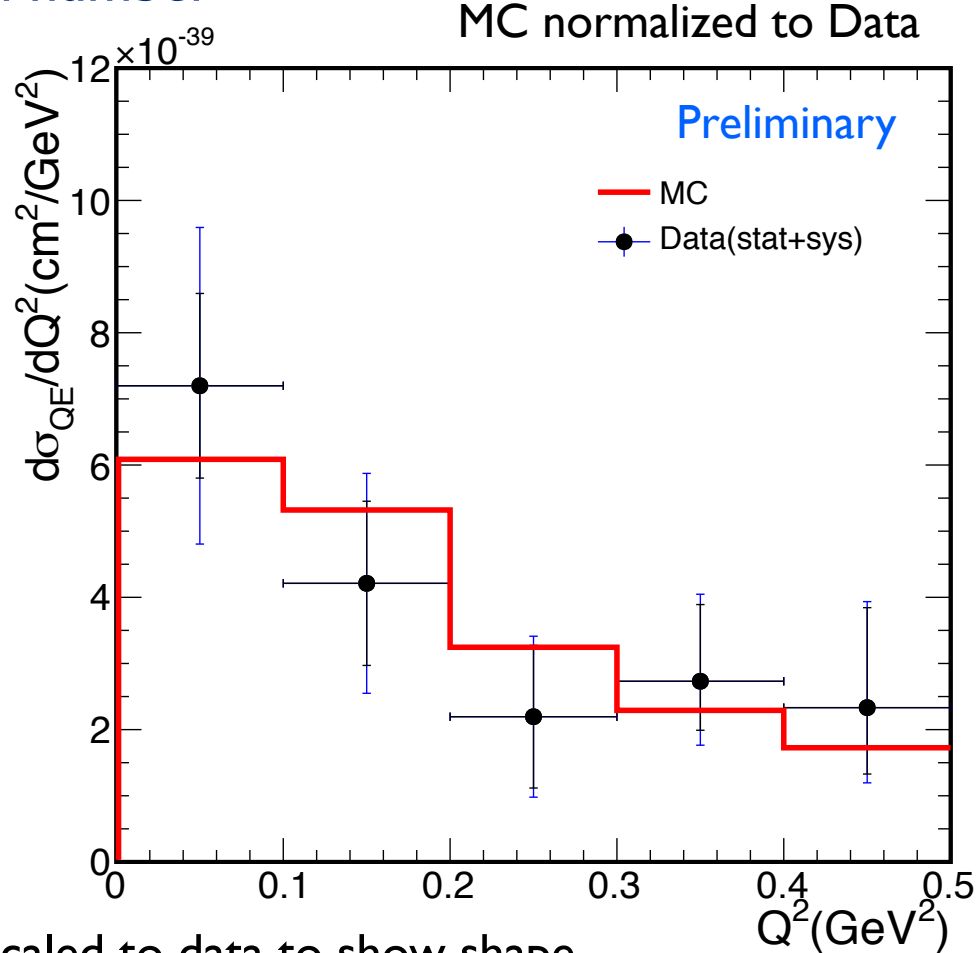
- M_{ij} Unfolding matrix
- N_{QE} rate of Quasi-Elastic interactions (Selected -background)
- ΔQ^2 bin width
- ϵ_i efficiency
- ϕ integrated flux
- T number of neutrons
- Unfolding is performed using a Bayesian method

Single Differential Cross Section

- Single differential cross-section is produced by unfolding the Q^2 distribution and normalization by efficiency, integrated flux and neutron number

Config 2

MC normalized to Data



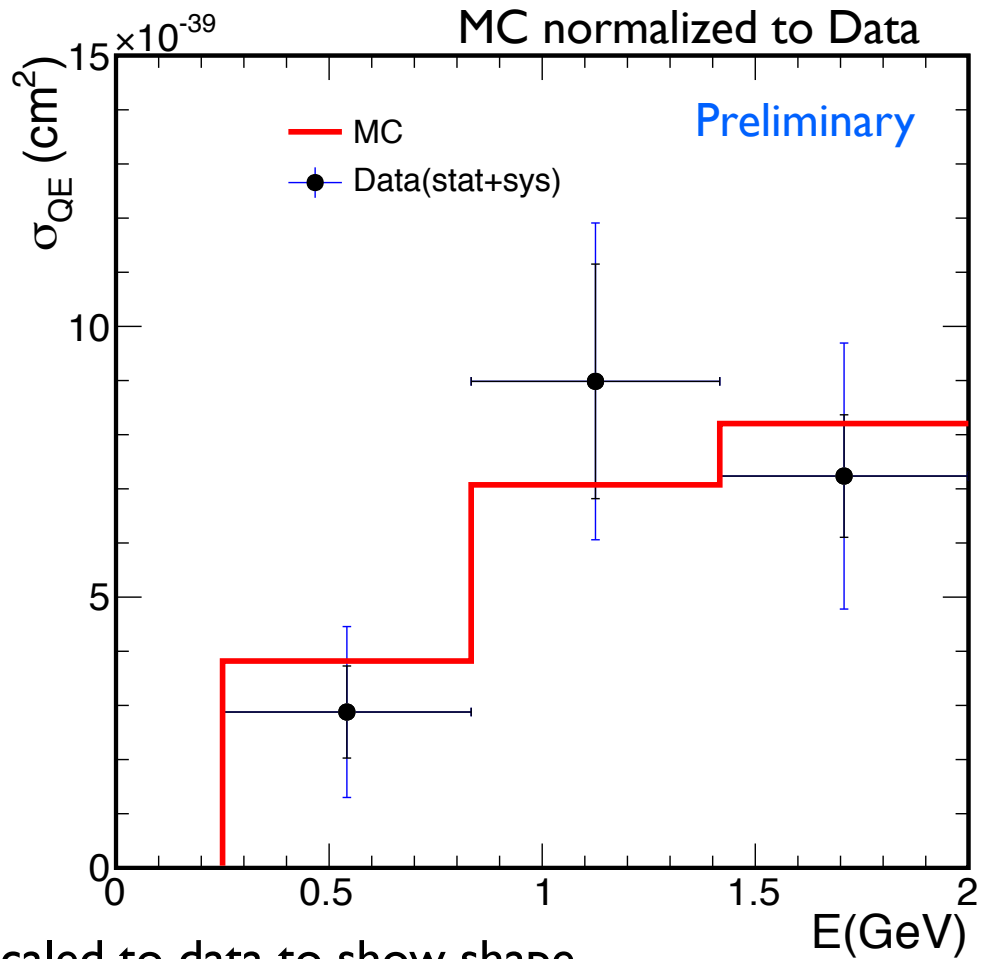
MC is scaled to data to show shape

Preliminary, pending a review of the flux uncertainty estimates

Cross Section as function of energy

- Cross-section is produced by unfolding the energy distribution, divide by the flux and normalization by efficiency and neutron number

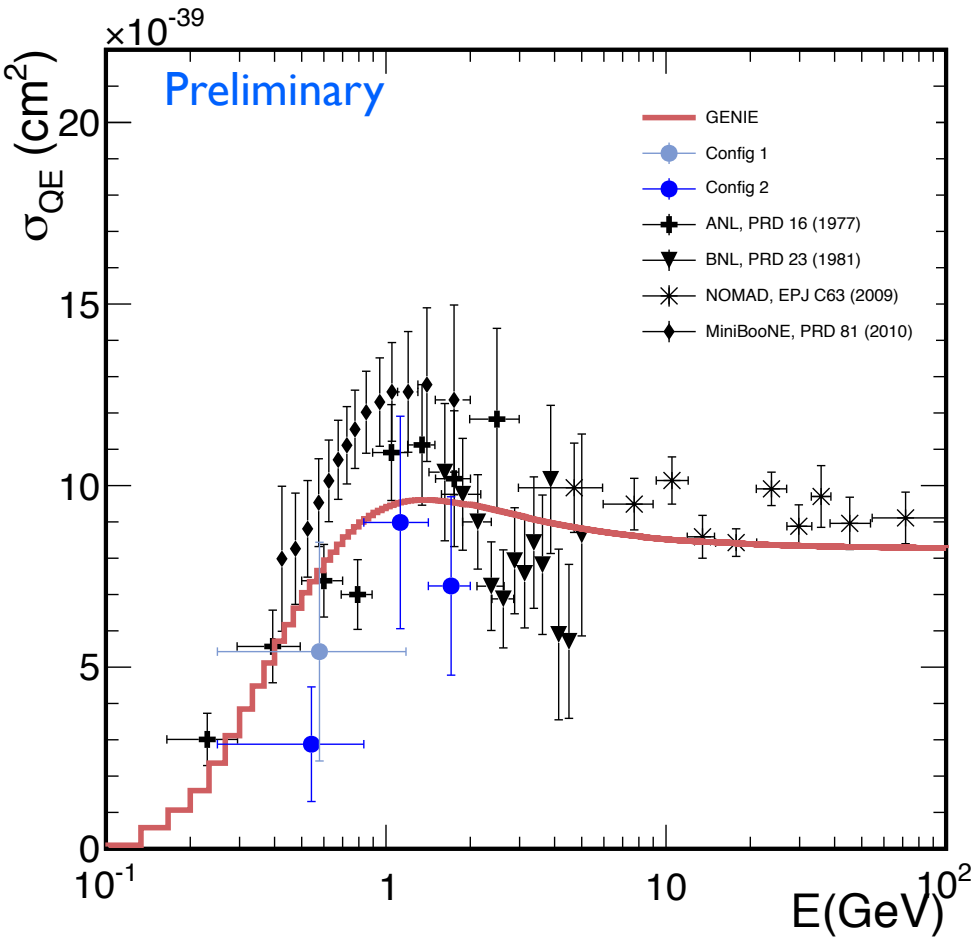
Config 2



MC is scaled to data to show shape
Preliminary, pending a review of the flux uncertainty estimates

Cross Section as function of energy

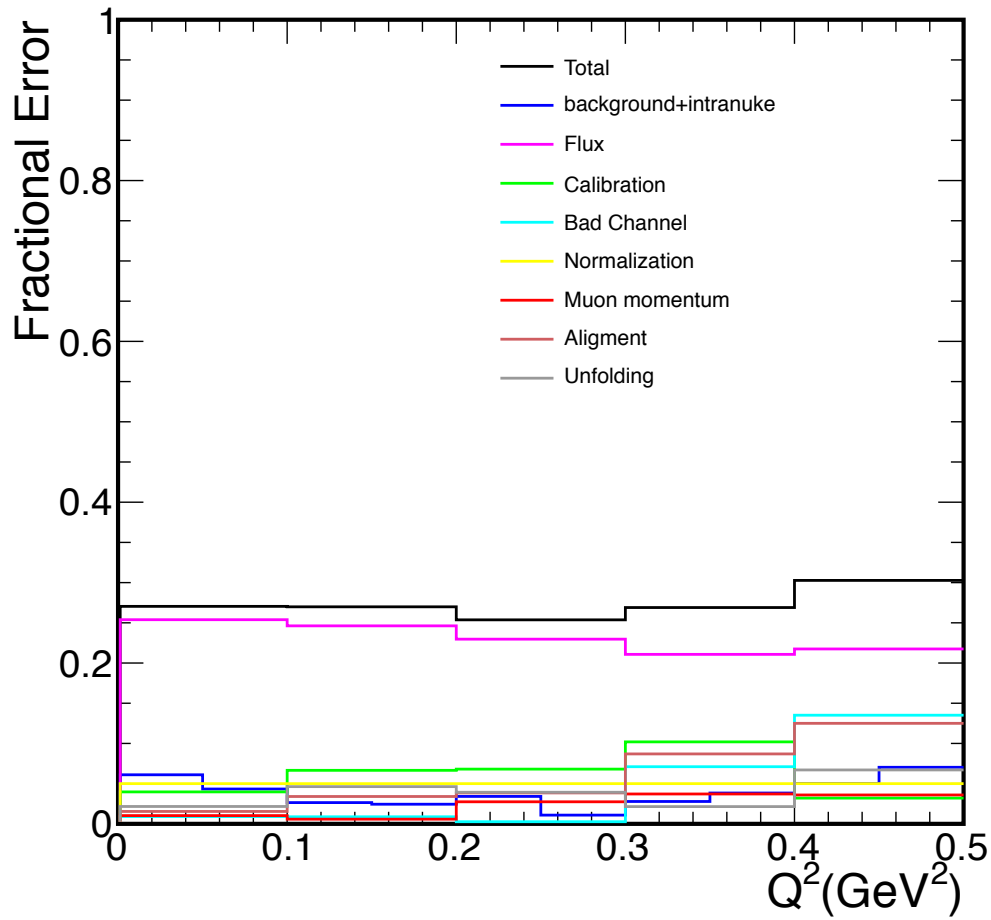
- ν_μ CC QE cross section measurement for both configurations compared with external data



Preliminary, pending a review of the flux uncertainty estimates

Systematic Uncertainties

- Systematic uncertainties prediction



Systematic uncertainties dominated by the flux systematic

Summary

- Detector Prototype provided a valuable input for assembly and analysis development
- Quasi-Elastic studies using the data from Detector Prototype is limited by statistics and pending a review of the flux uncertainty estimates
- We continue to study neutrino data from Prototype to test analysis procedures for NOvA
- Near Detector installation start summer 2013
- First Far Detector beam data coming soon!