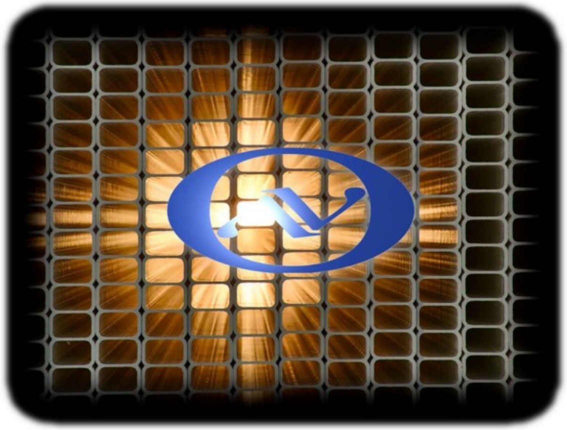
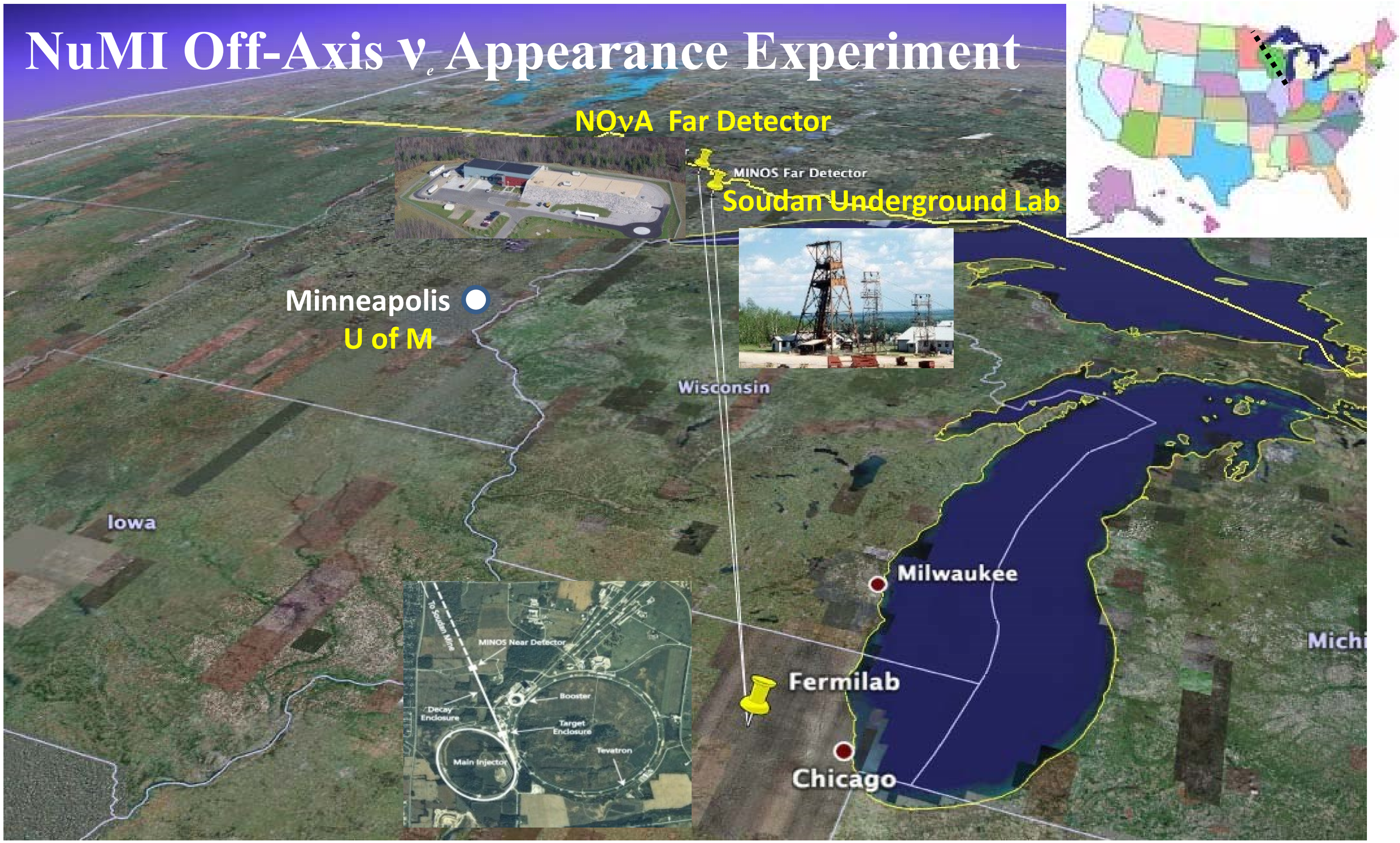
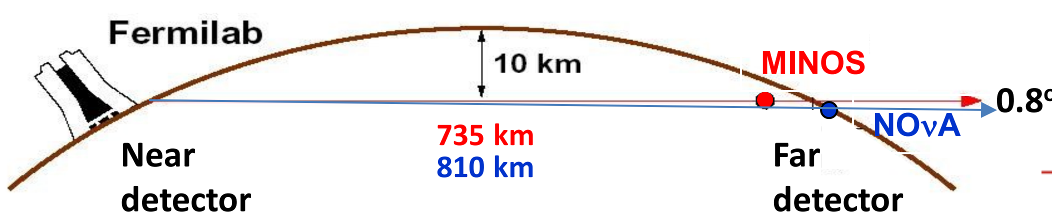


ν_μ CC QE results from the NOvA prototype detector

Jarek Nowak and Minerba Betancourt

NOνA – The Long-Baseline Neutrino Oscillation Experiment.



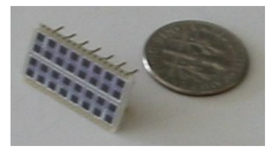


NOvA Collaboration

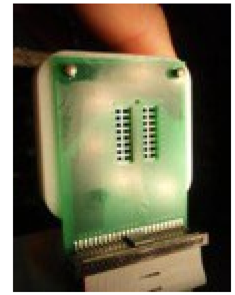
Here I will briefly describe NOvA technology. For a detail overview of NOvA experiment see talk by M. Frank on Thursday.

The NOvA detectors

- 14 kton Far Detector
  - >70% active detector.
  - 344 000 detector cells read by APDs.
- 300 ton Near Detector
  - 18,000 cells (channels).
- Good for e^- vs π^0 identification.



32-pixel APD

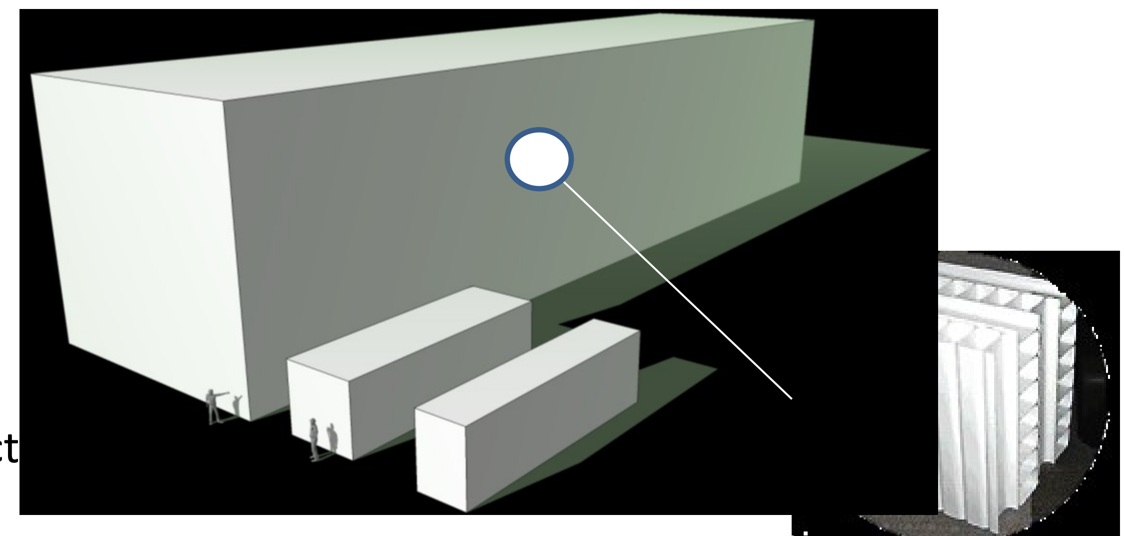


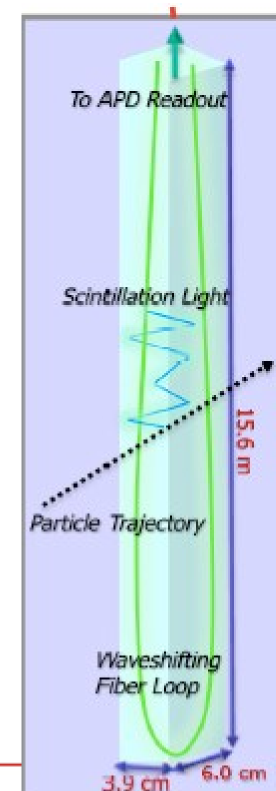
Both ends of a fiber to one pixel

Far detector
14 kton
928 planes

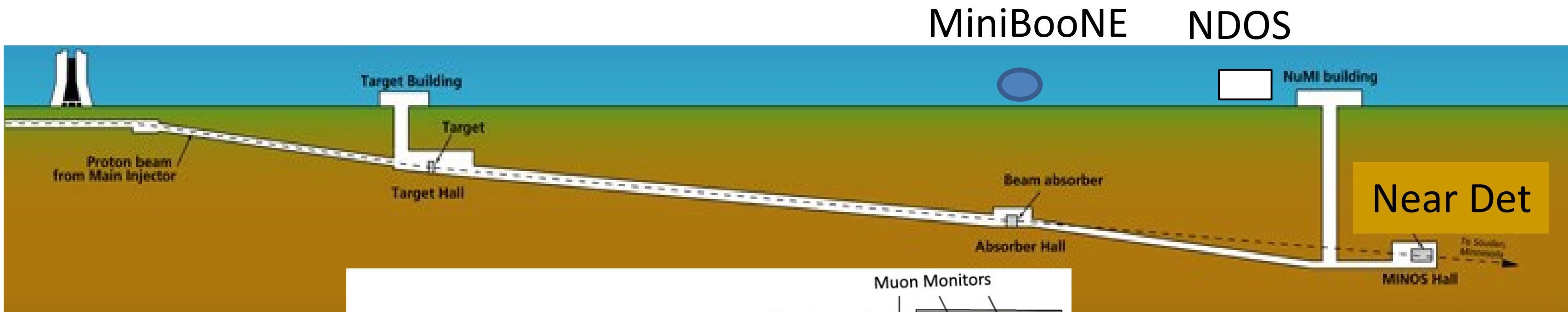
Near detector
300 ton

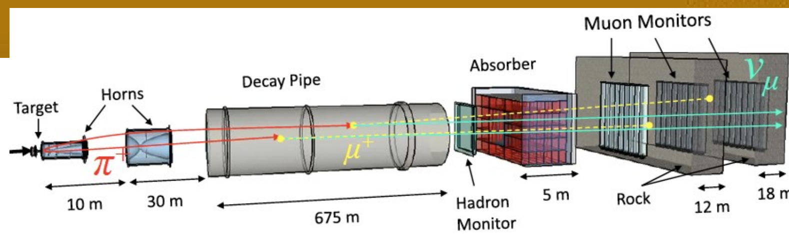
Prototype detect
200 ton





NuMI beamline (Neutrinos at the Main Injector)



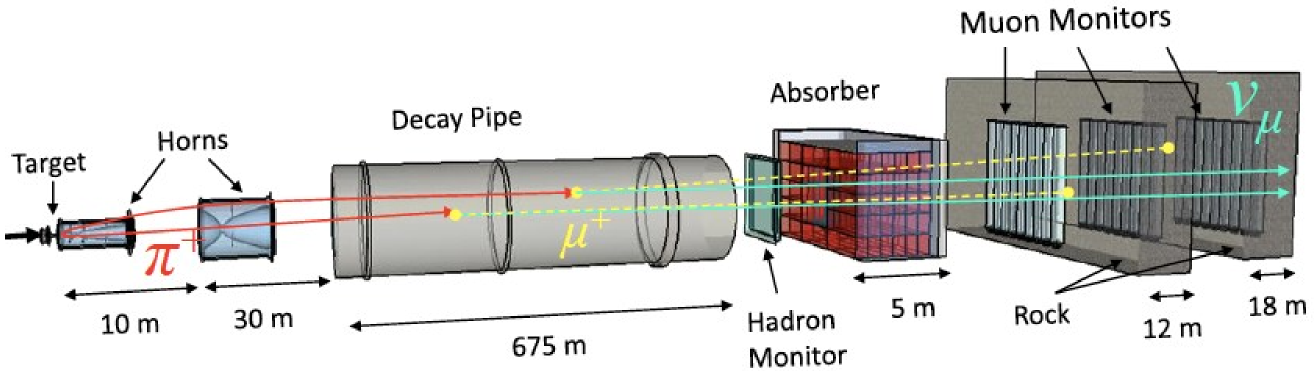


NuMI before upgrade

Linac: 750 keV – 400 MeV
Booster: 400 MeV – 8 GeV
Main Injector: 8 GeV – 120 GeV
Slip-stack 11 booster batches
2 batches to antiproton source
9 batches to NuMI

Cycle length is 2.2s
Typical peak NuMI beam power
~330 kW in mixed mode

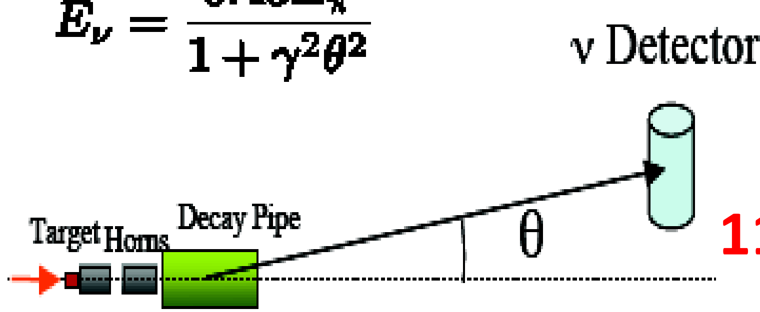
Neutrino Production



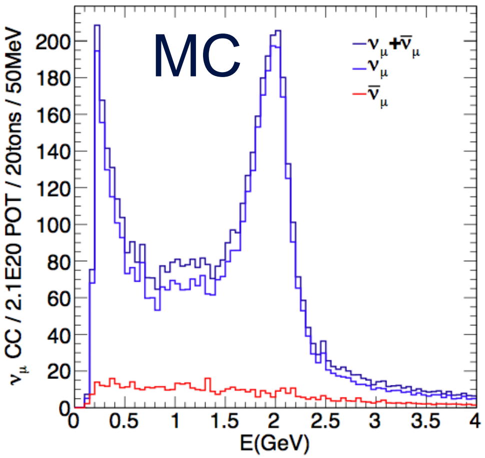
– Detector Prototype 110 mrad off-axis

Detector Prototype energy spectrum

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

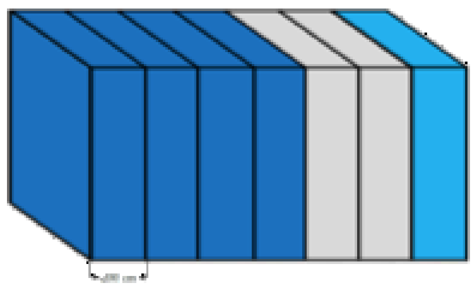


110 mrad

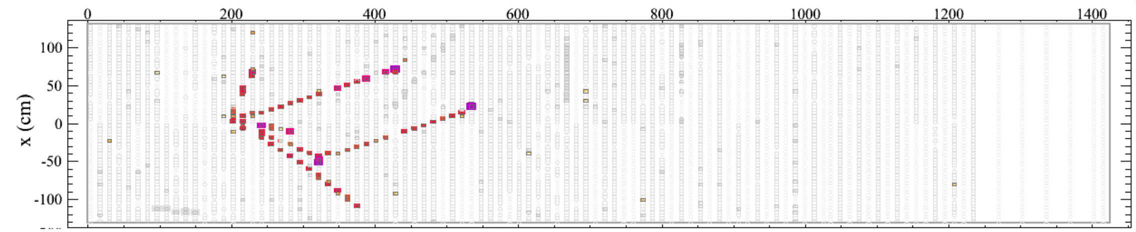


Detector Prototype Configurations

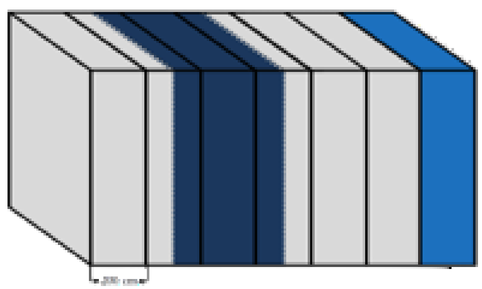
Config 1

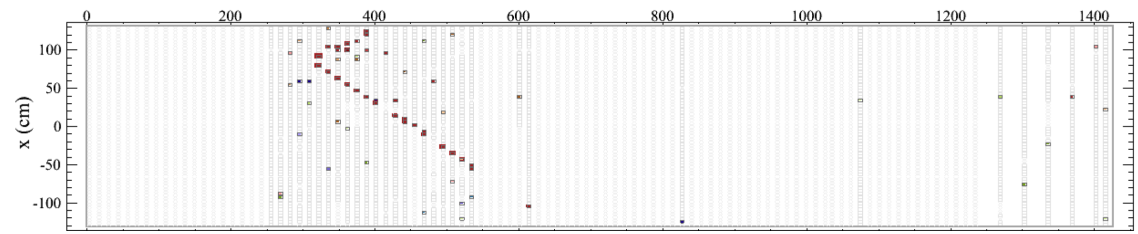


Data



Config 2





- Fully instrumented
- Mostly instrumented
- Partially instrumented
- Uninstrumented

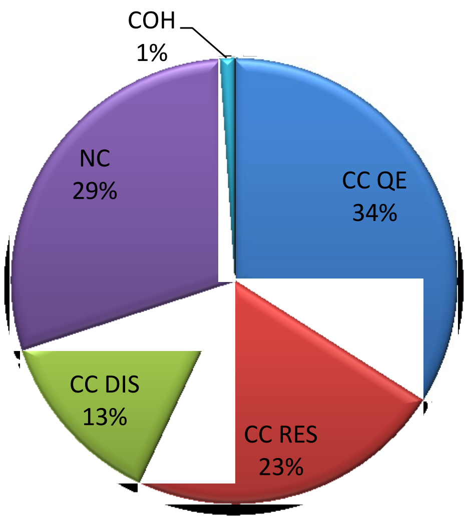
APD tests helped:

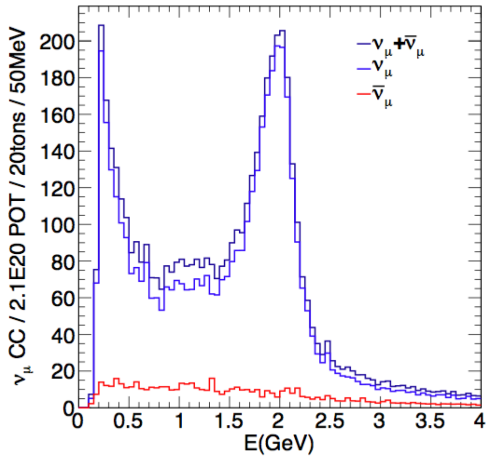
- Developed surface coating for APDs to protect the surface from potential contact with contaminants
- Added an active air drying system to keep out condensation due to cooling

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

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

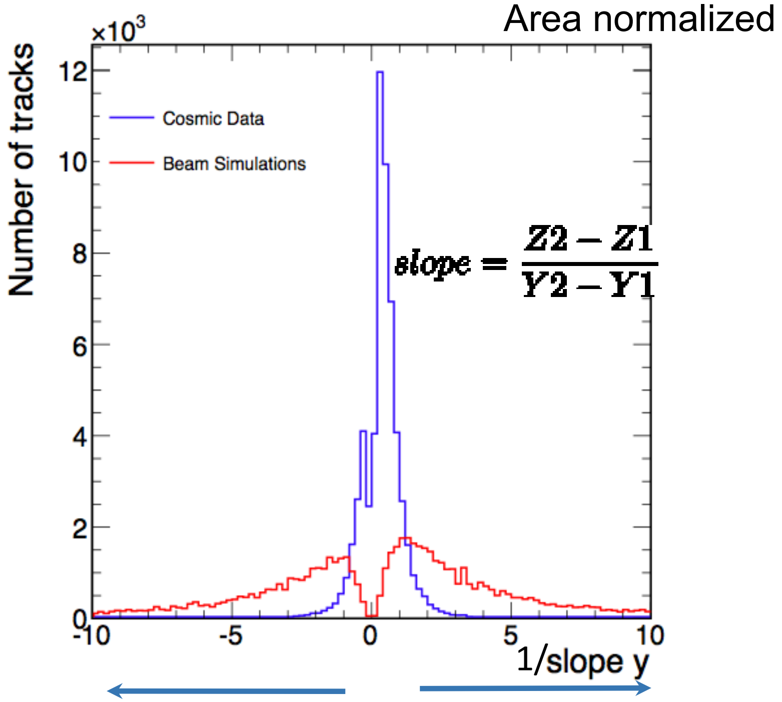




Cosmic Background – track slope cut

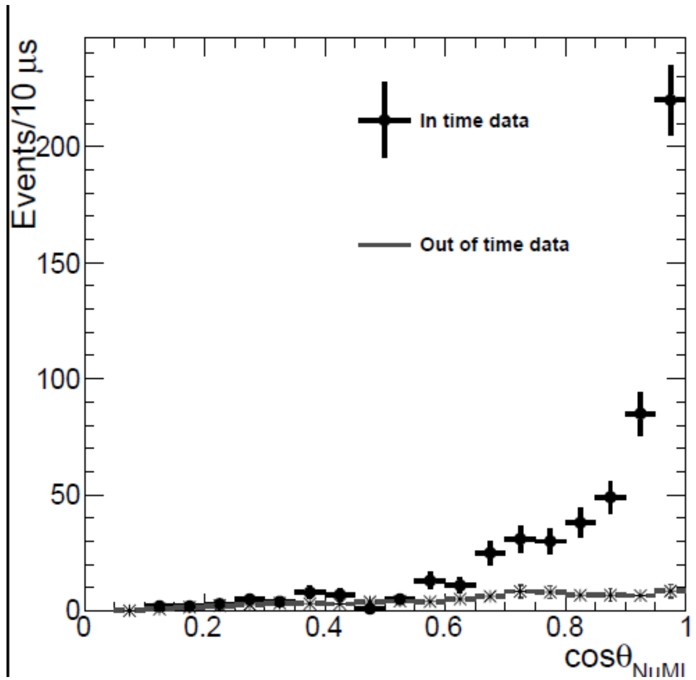
- **We use a selection to reject the cosmic background: the slope of the tracks in the vertical view and containment**

Slope of the tracks in the vertical view



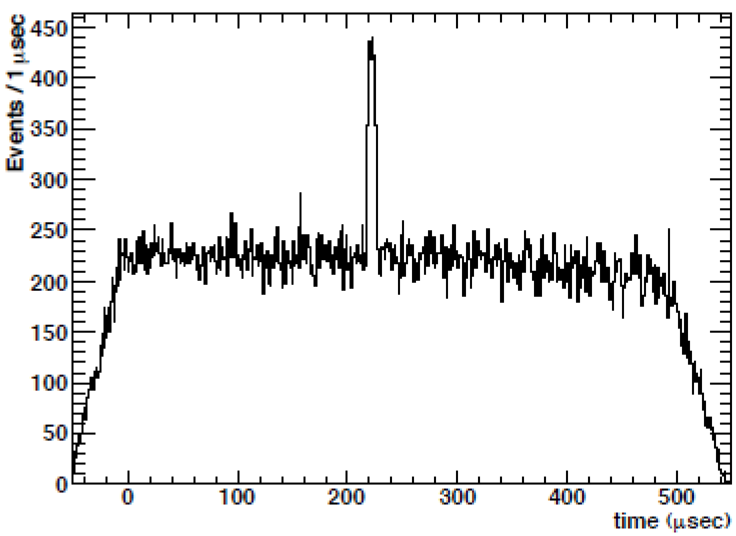
slope>1 and slope <-1

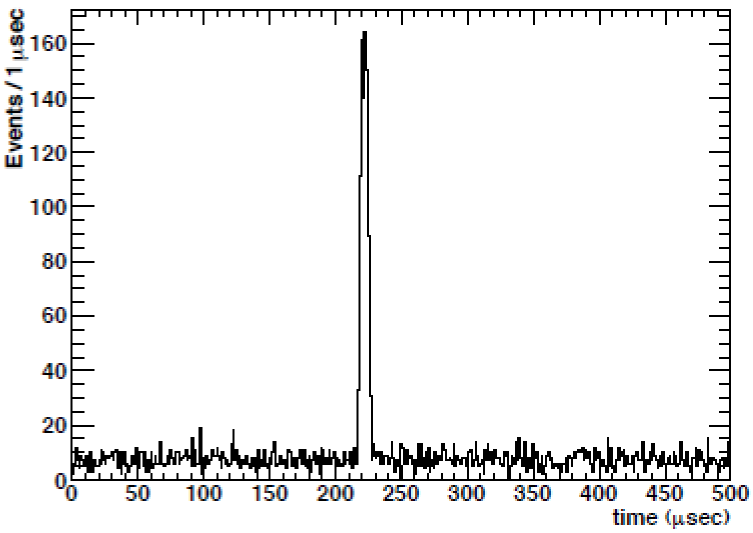
Reconstructed particle tracks angle with respect to the beam direction



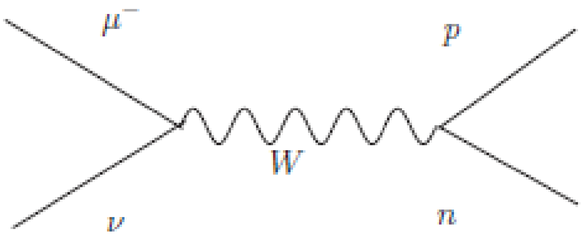
Cosmic Background - timing peak

- **We use a selection to reject the cosmic background: the slope of the tracks in the vertical view and containment**





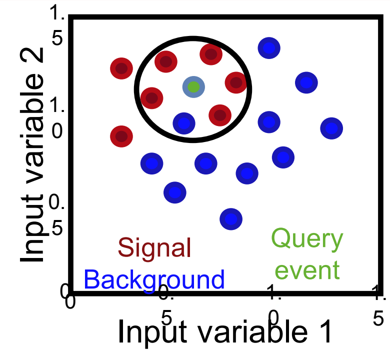
Quasi-Elastic Selection



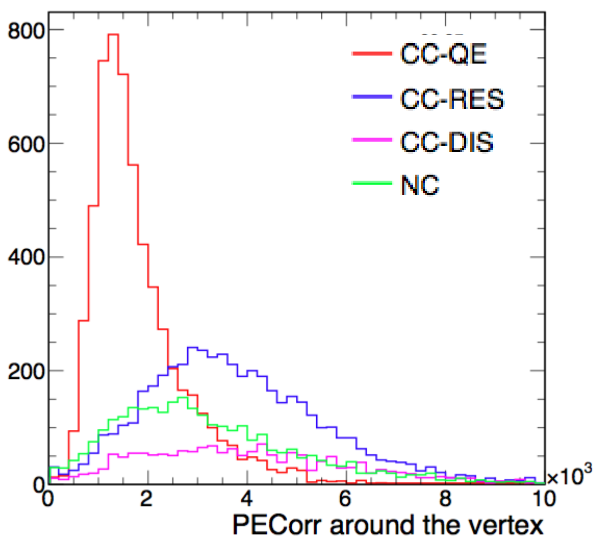
- Pre-election cuts:
  - Event within 10 microsecond beam spill
  - Interaction point 50cm from the edge of the detector
  - One and only one reconstructed track
  - The slope of the tracks is not near vertical (cosmic rejection)
  - Track does not exit the detector
- Quasi-Elastic interaction identification using a k Nearest Neighbors (kNN) algorithm
  - Studies in MC use channel masks for a partially instrumented detector

CCQE PID with kNN classifier

- The k Nearest Neighbor (kNN) algorithm with three input variables

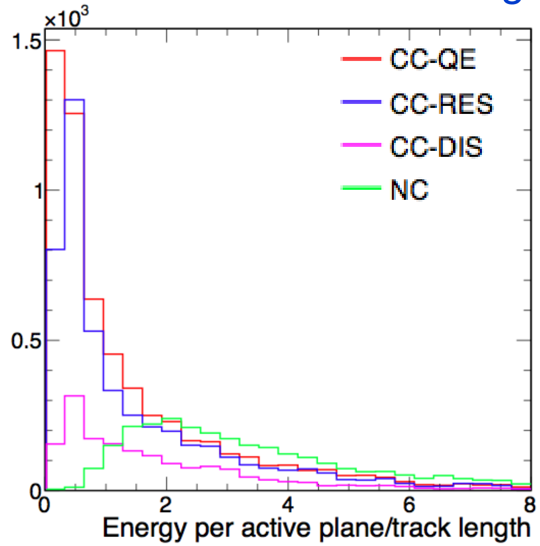


Energy around the vertex



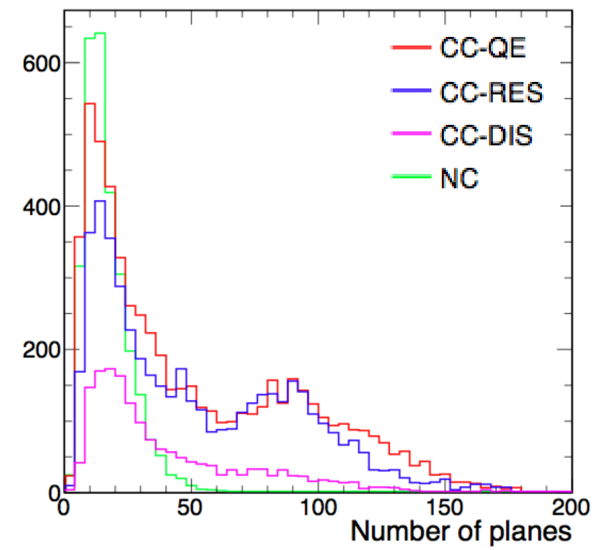
RES, DIS and NC deposit more energy around the vertex

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

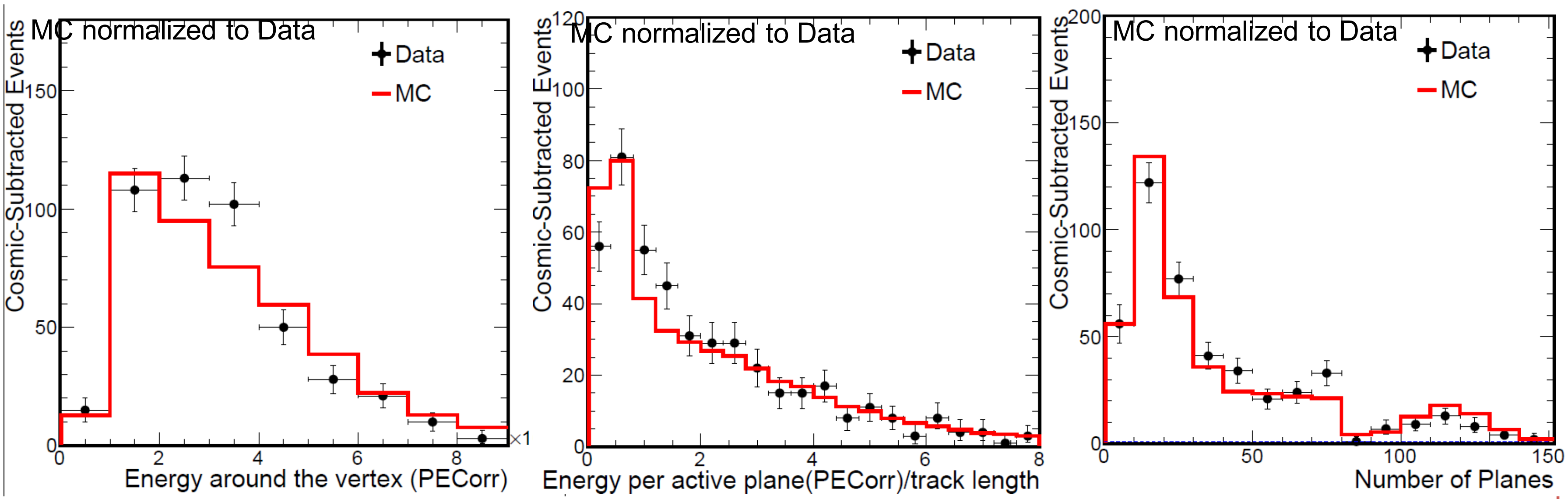
CCQE PID with kNN classifier - Data

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

Energy around the vertex

Mean energy per active plane normalized to track length

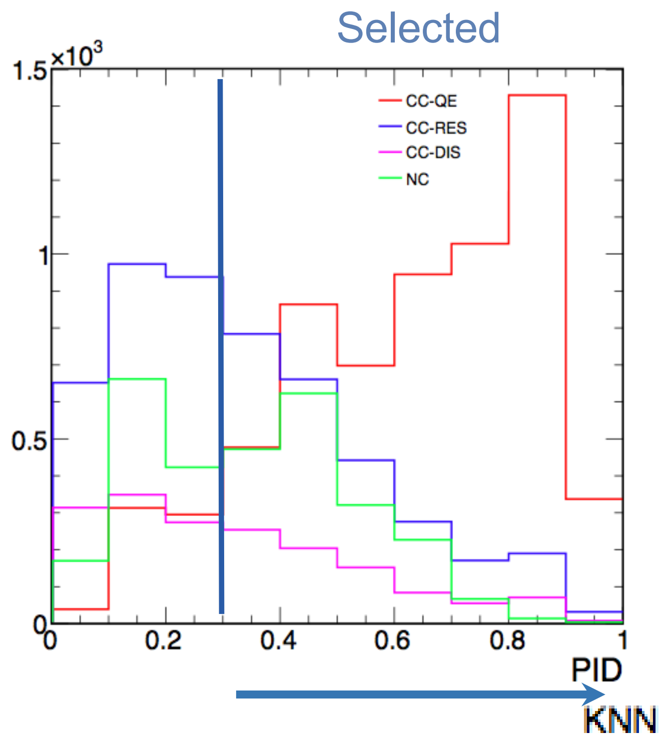
Number of planes

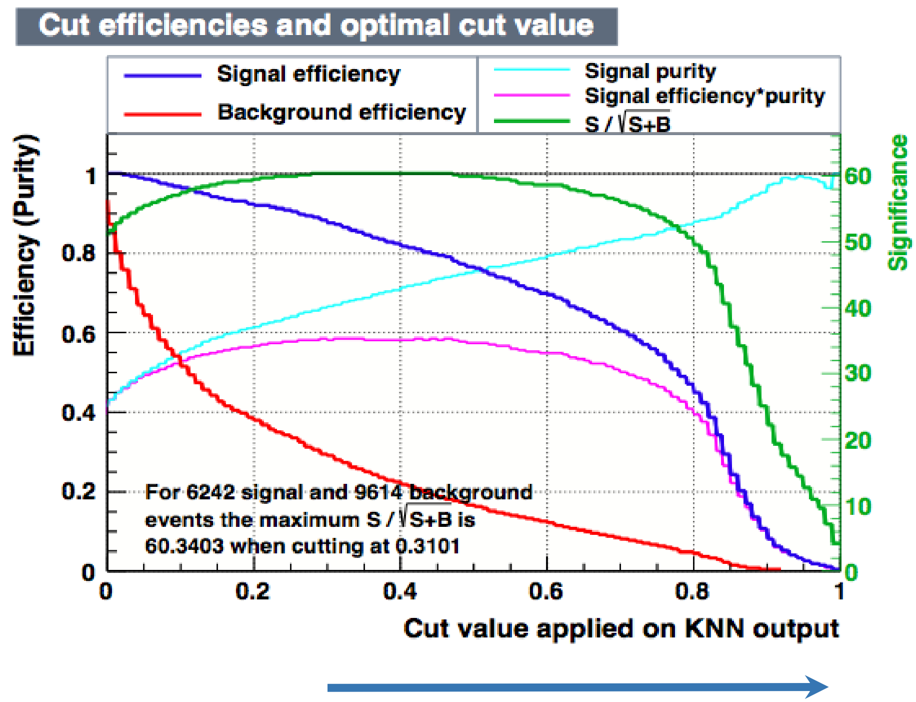


Beam candidates after cosmic background subtraction and Monte Carlo simulation for preselected events

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



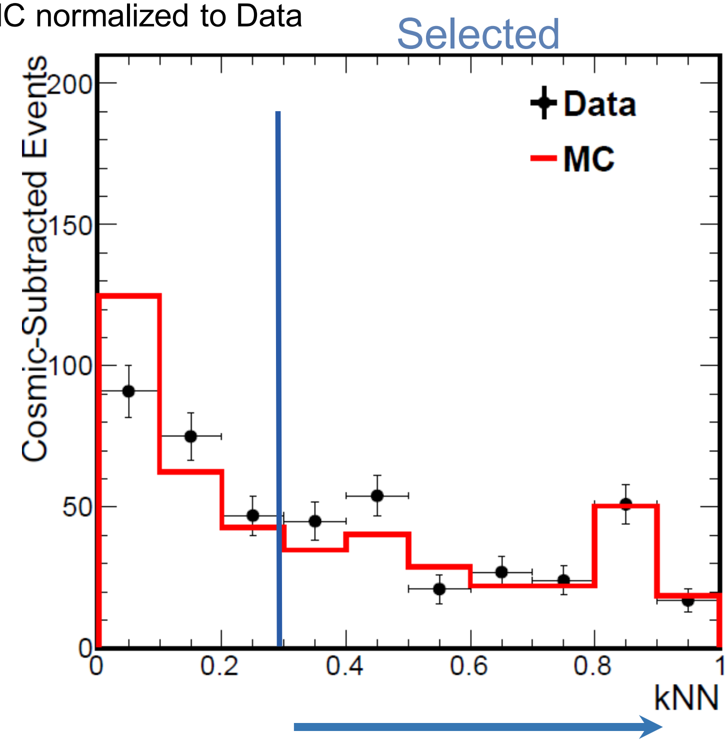


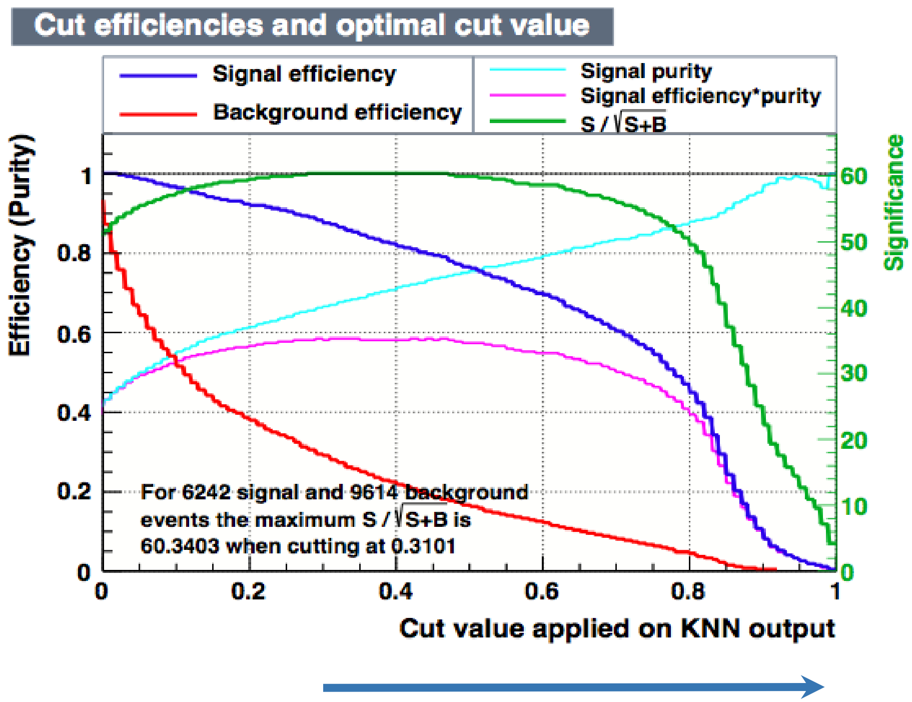
- For kNN>0.3, events have 65% purity and 85% efficiency for the partially instrumented detector for both configurations

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

MC normalized to Data





- 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

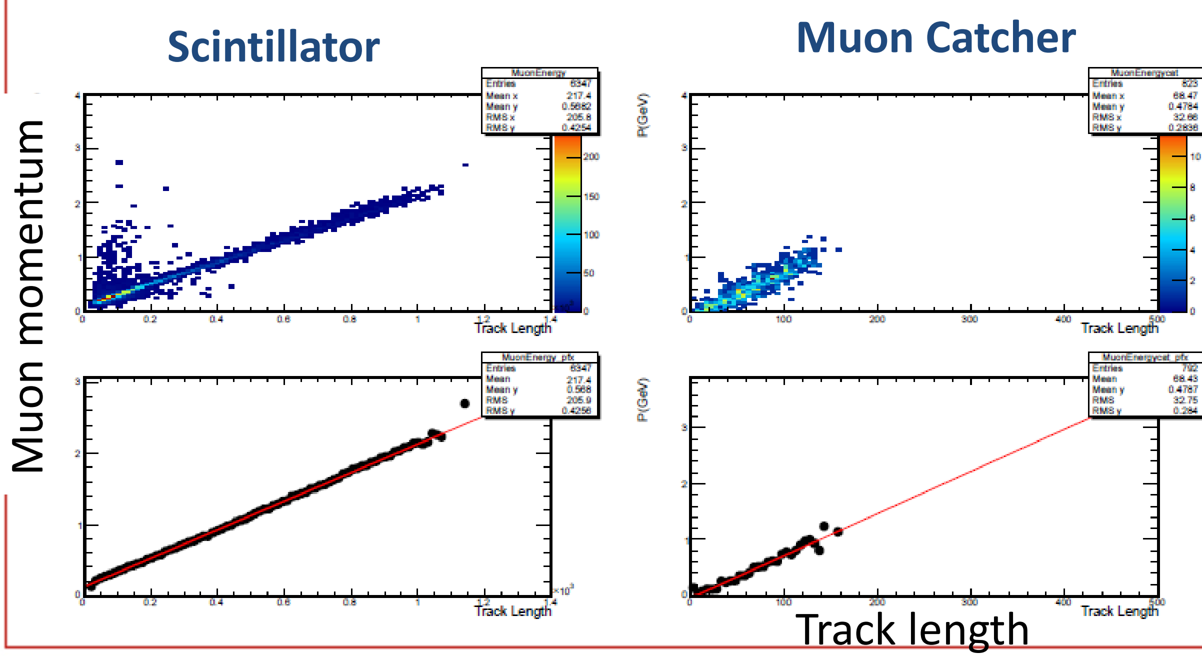
- Neutrino energy is reconstructed from the length of the track and its angle from the beam direction

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

Four momentum is reconstructed using

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

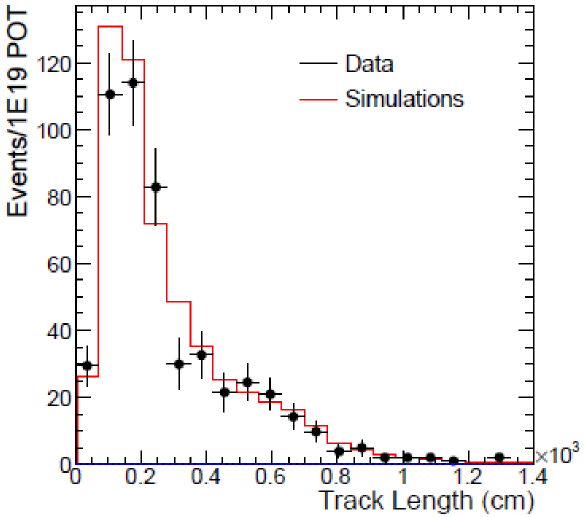
$$M' = M_n - E_B \quad and \quad E_B = 25MeV$$

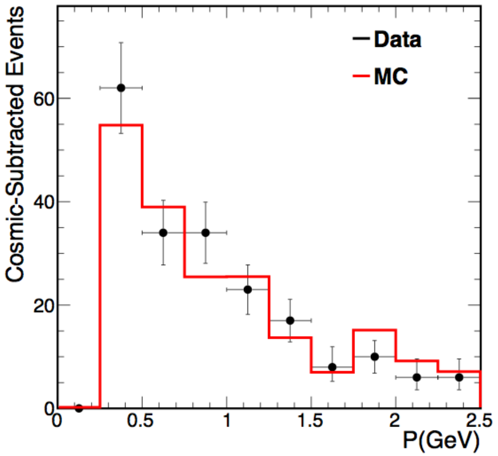


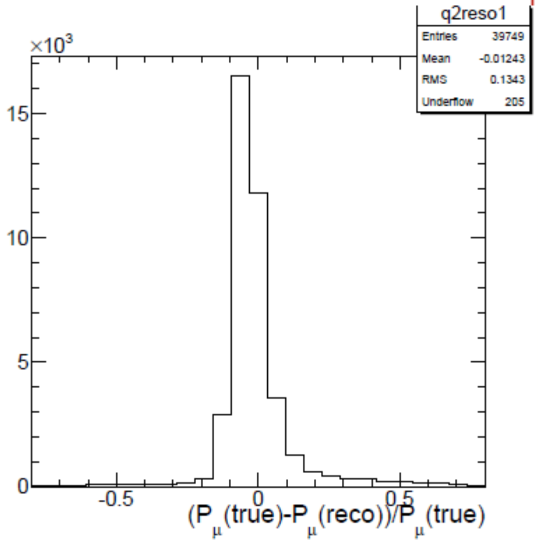
Muon Energy was obtain from simulations of the QE interactions in the detector

Muon momentum reconstruction

- ν_μ CC QE selected events after cosmic background subtraction



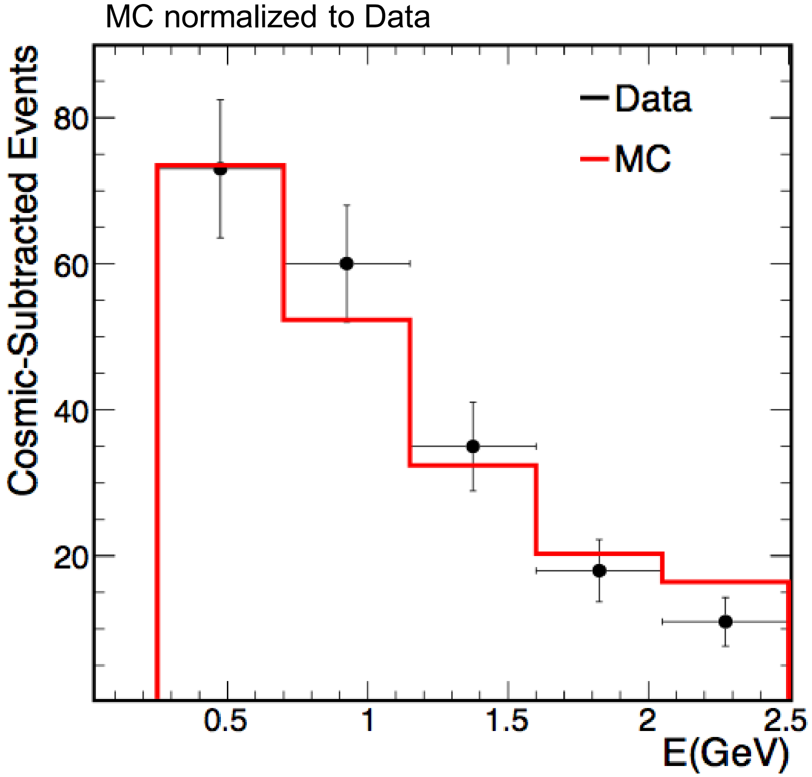


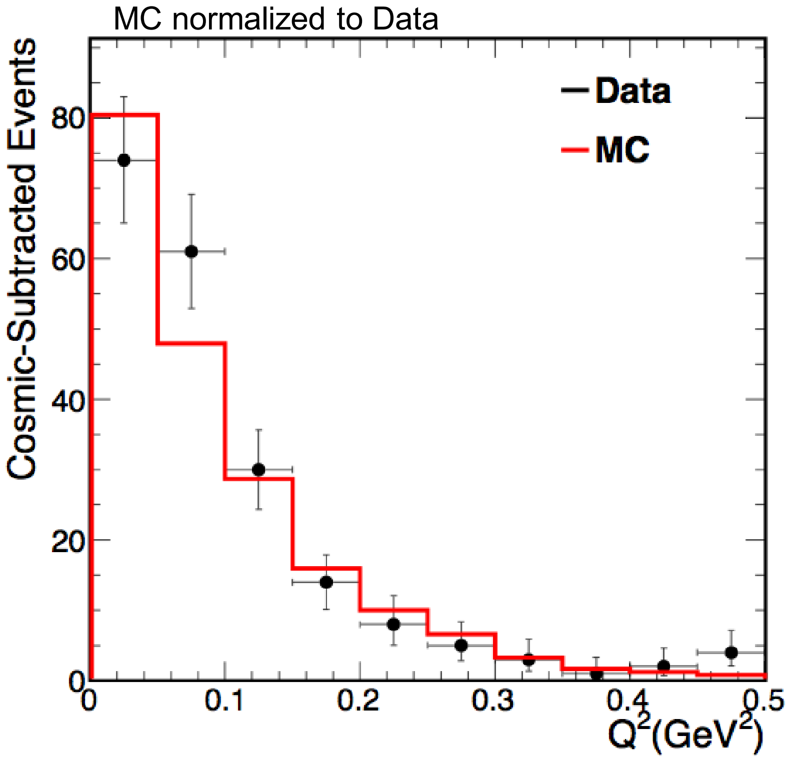


Good agreement for the track length

13% muon momentum resolution

Event rate (E_ν and Q^2)



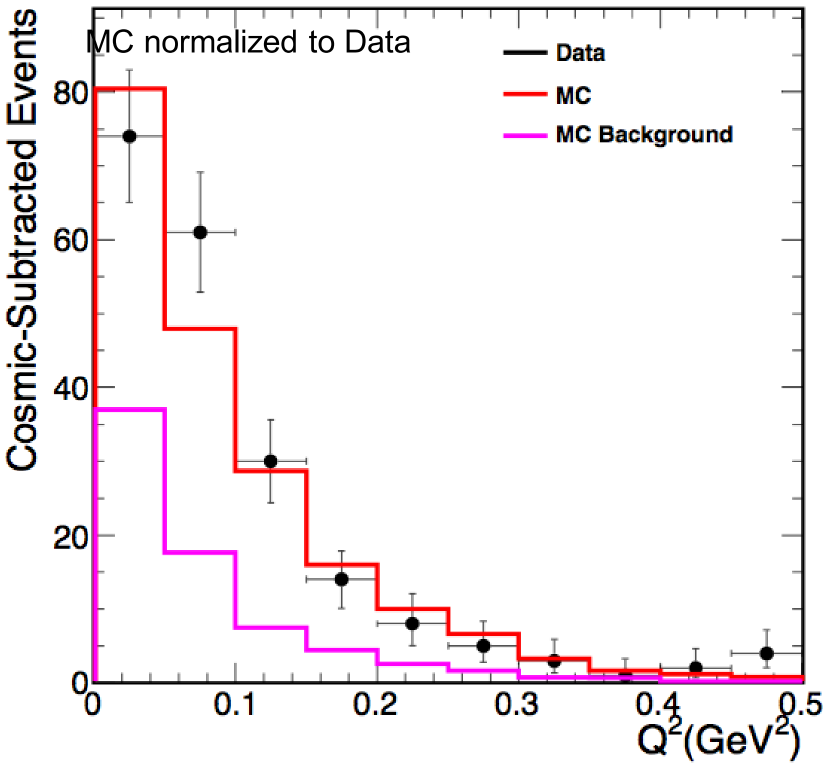


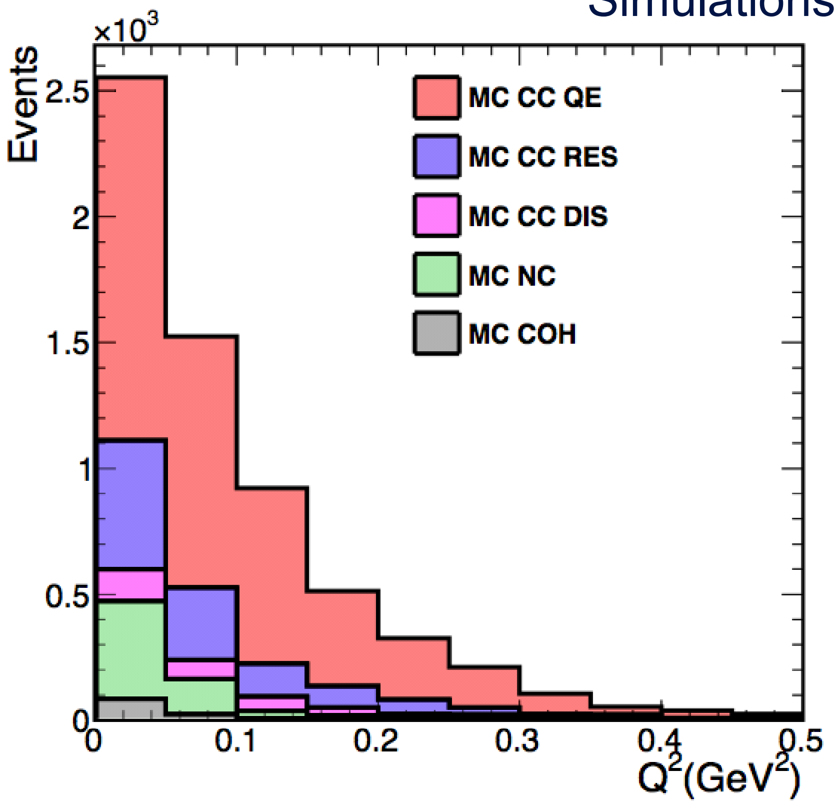
ν_μ CC QE selected events after cosmic background subtraction

Four Momentum Transfer

Selected CC QE four momentum transfer

Simulations

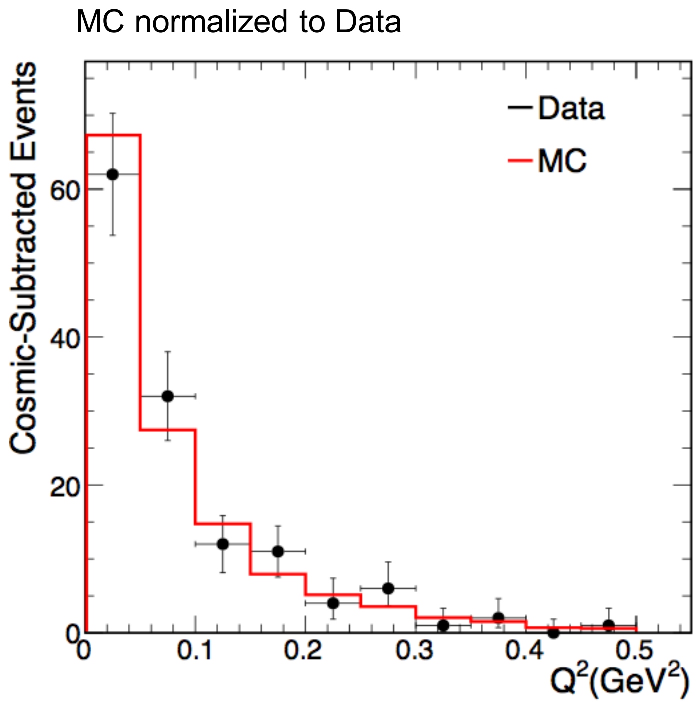


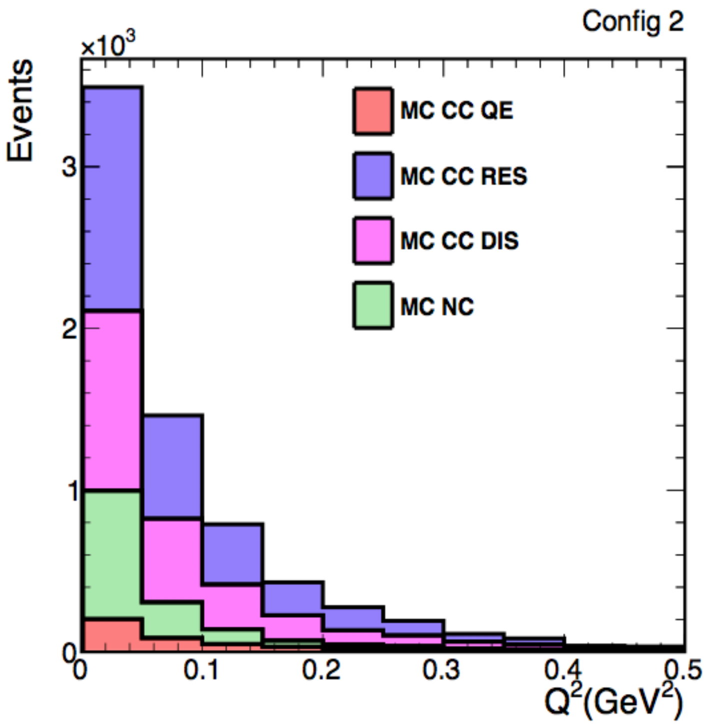


ν_μ CC QE selected events after cosmic background subtraction and MC simulation

Background Study

- Background dominated data with two reconstructed tracks from the interaction was used to cross check the Monte Carlo for background events
- Longest track used to determine the energy and four momentum transfer



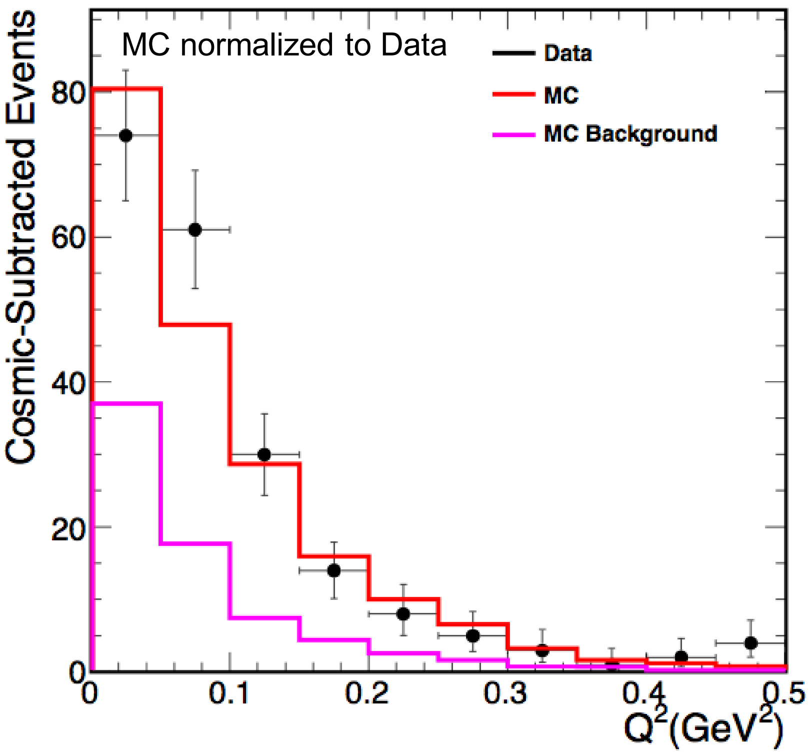


Background data agrees with MC simulations

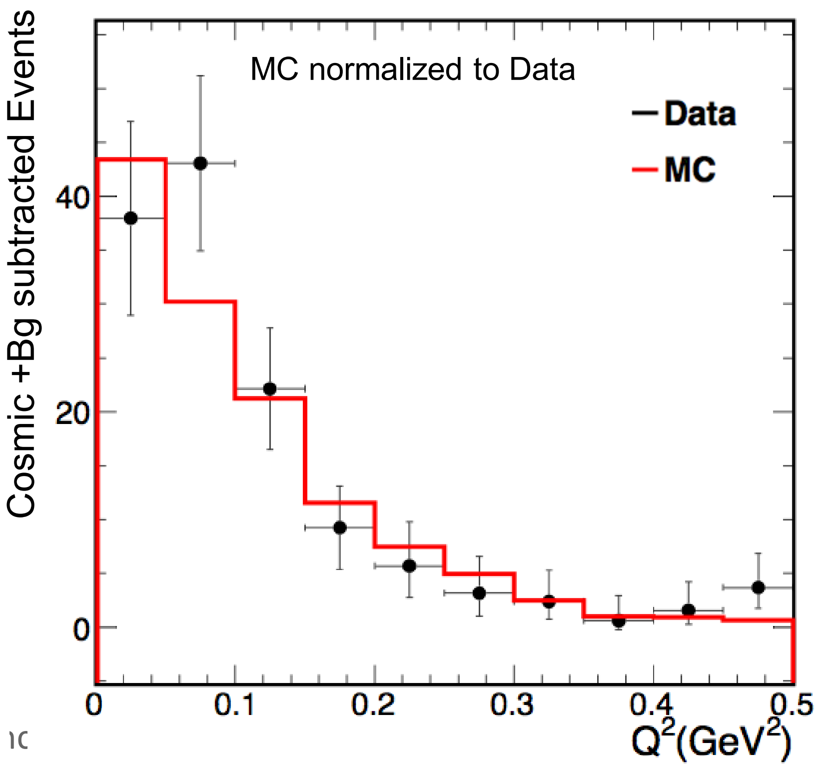
Background Subtracted Q^2

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

Four momentum transfer with background



After background subtraction



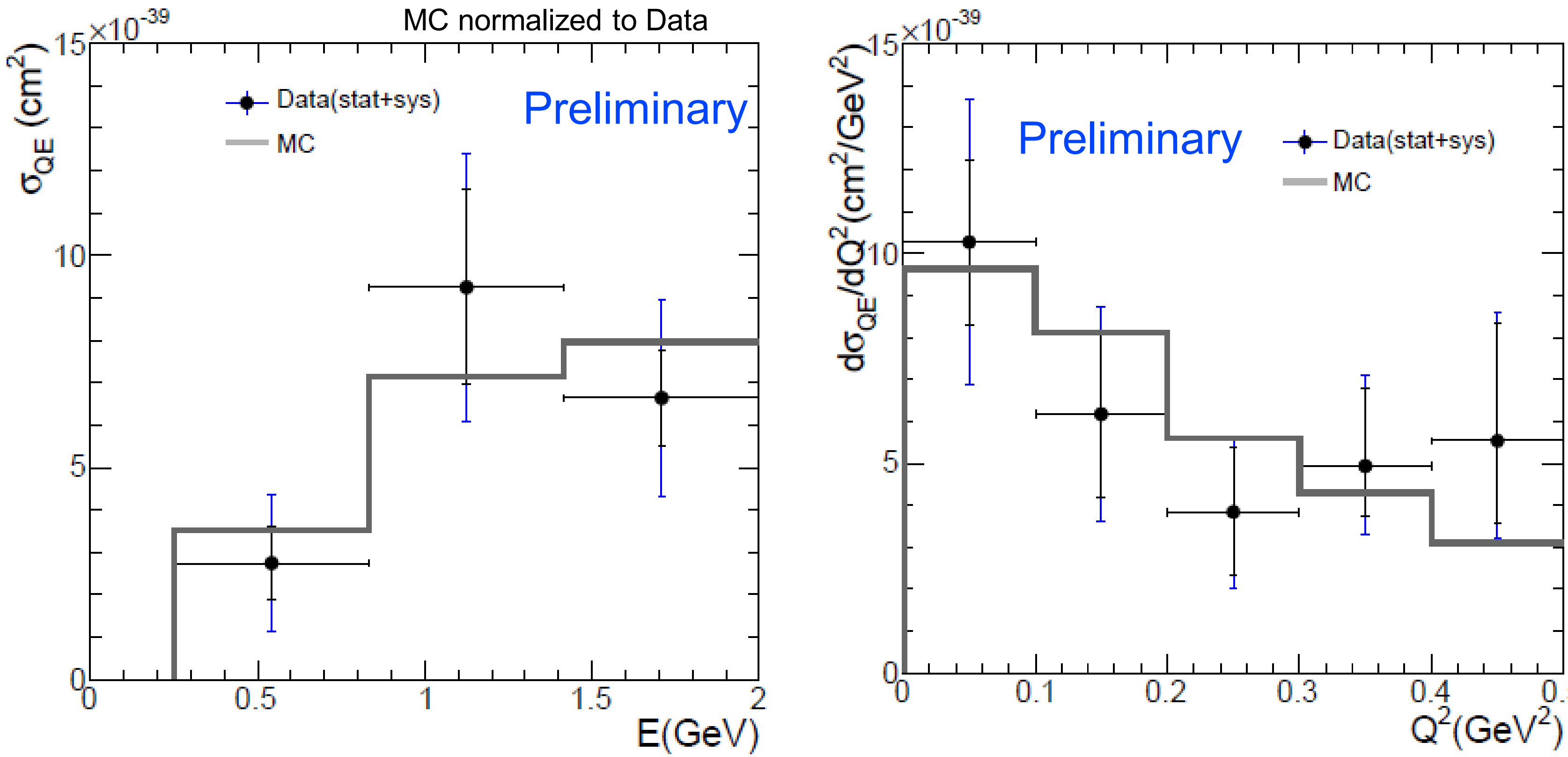
Single Differential Cross Section calculation

- Single differential cross section

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

- 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

Cross sections results show good agreement with MC shape prediction



Cross-section results

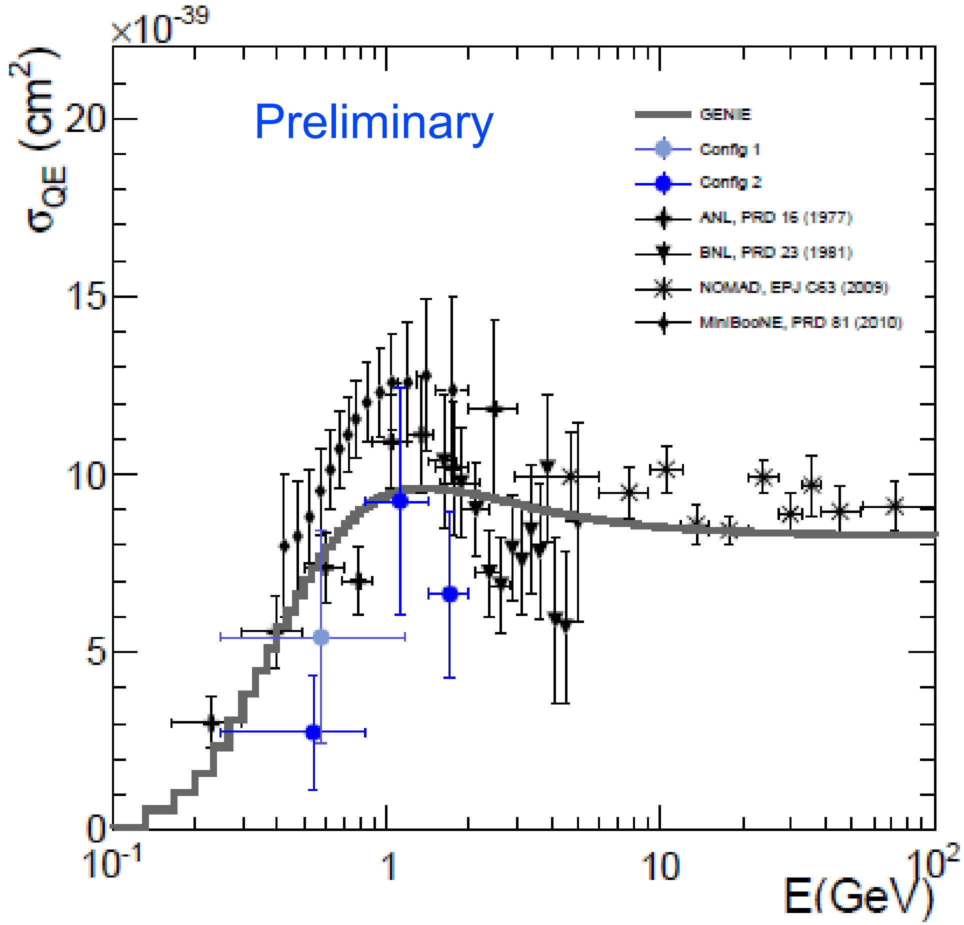


TABLE II. Cross section as a function of E.

E(GeV)	$\sigma(cm^2)$	$stat$	sys	$total \quad error$
0.25-0.8	2.7×10^{-39}	0.9×10^{-39}	1.9×10^{-39}	2.1×10^{-39}
0.8-1.4	9.2×10^{-39}	2.3×10^{-39}	2.9×10^{-39}	3.7×10^{-39}
1.4-2.0	6.6×10^{-39}	1.1×10^{-39}	3.0×10^{-39}	3.2×10^{-39}

- NOvA results favor lower values of the Cross sections.
- Results are statistically limited.
- Also significant uncertainly from the flux prediction.

Conclusions

- The cross section measurement show tension with MiniBooNE results.
- The NOvA prototype detector showed that the technology will be useful for precise cross section measurement with the NOvA Near Detector .
- The draft of the manuscript is under internal review.