Neutrino Scattering Measurements in the NOνA Experiment

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Argonne National Laboratory

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Beijing, China
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The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

A growing collaboration of over 180 scientists and engineers from 36 institutions and 7 countries.

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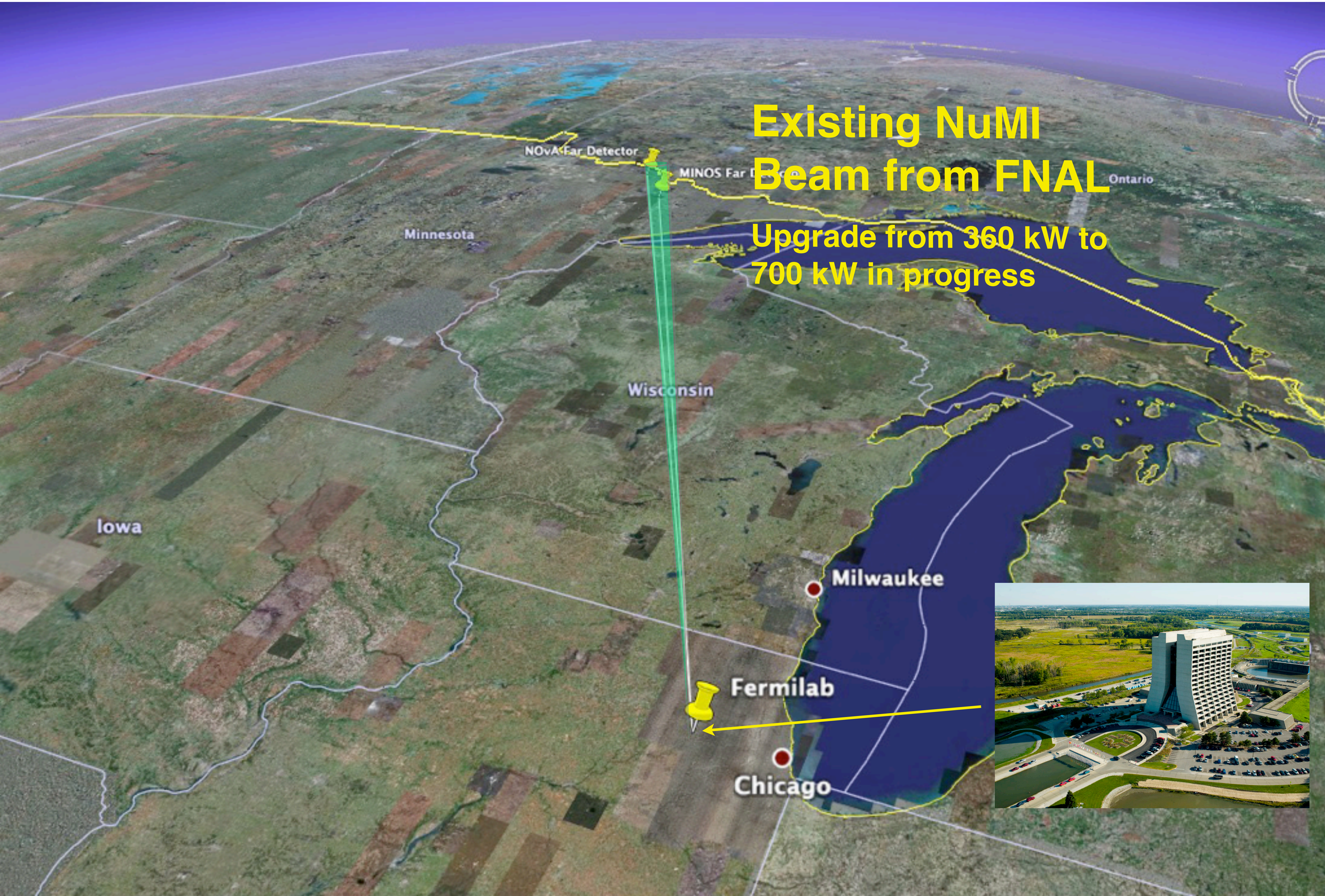

Existing NuMI Beam from FNAL

Upgrade from 360 kW to 700 kW in progress

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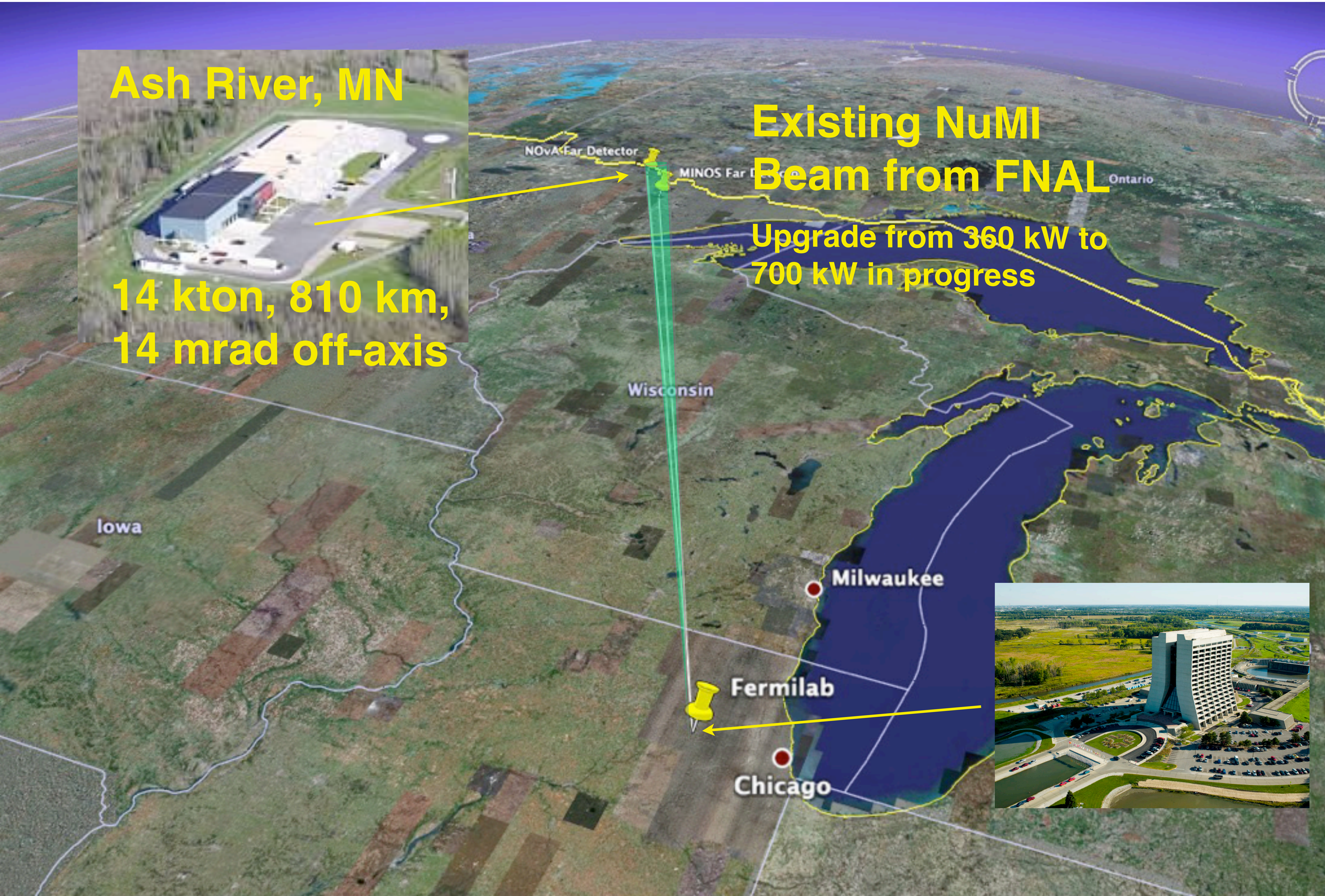

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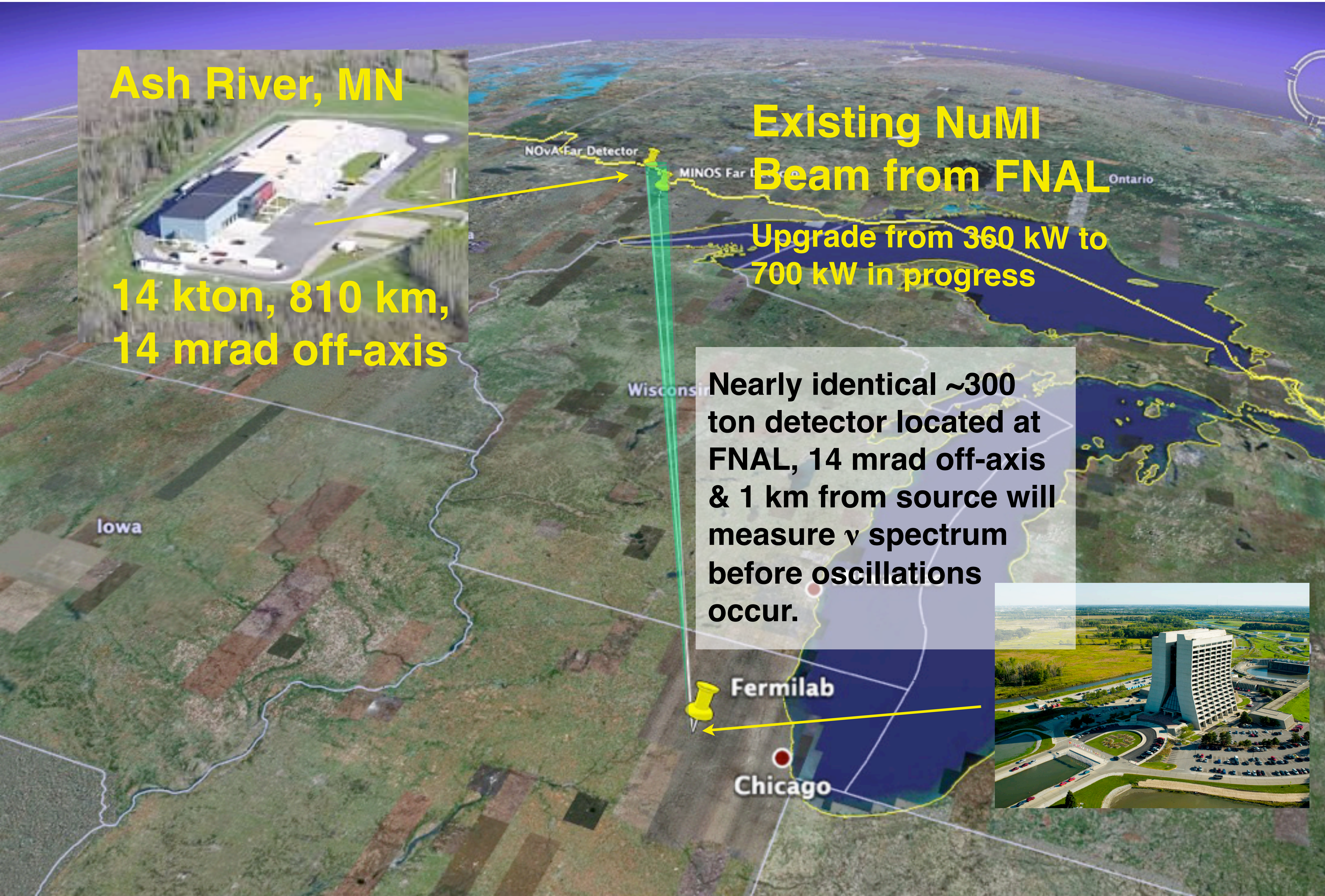


Ash River, MN

14 kton, 810 km,
14 mrad off-axis

Existing NuMI Beam from FNAL

Upgrade from 360 kW to 700 kW in progress

Nearly identical ~300 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

Ash River, MN

14 kton, 810 km, 14 mrad off-axis

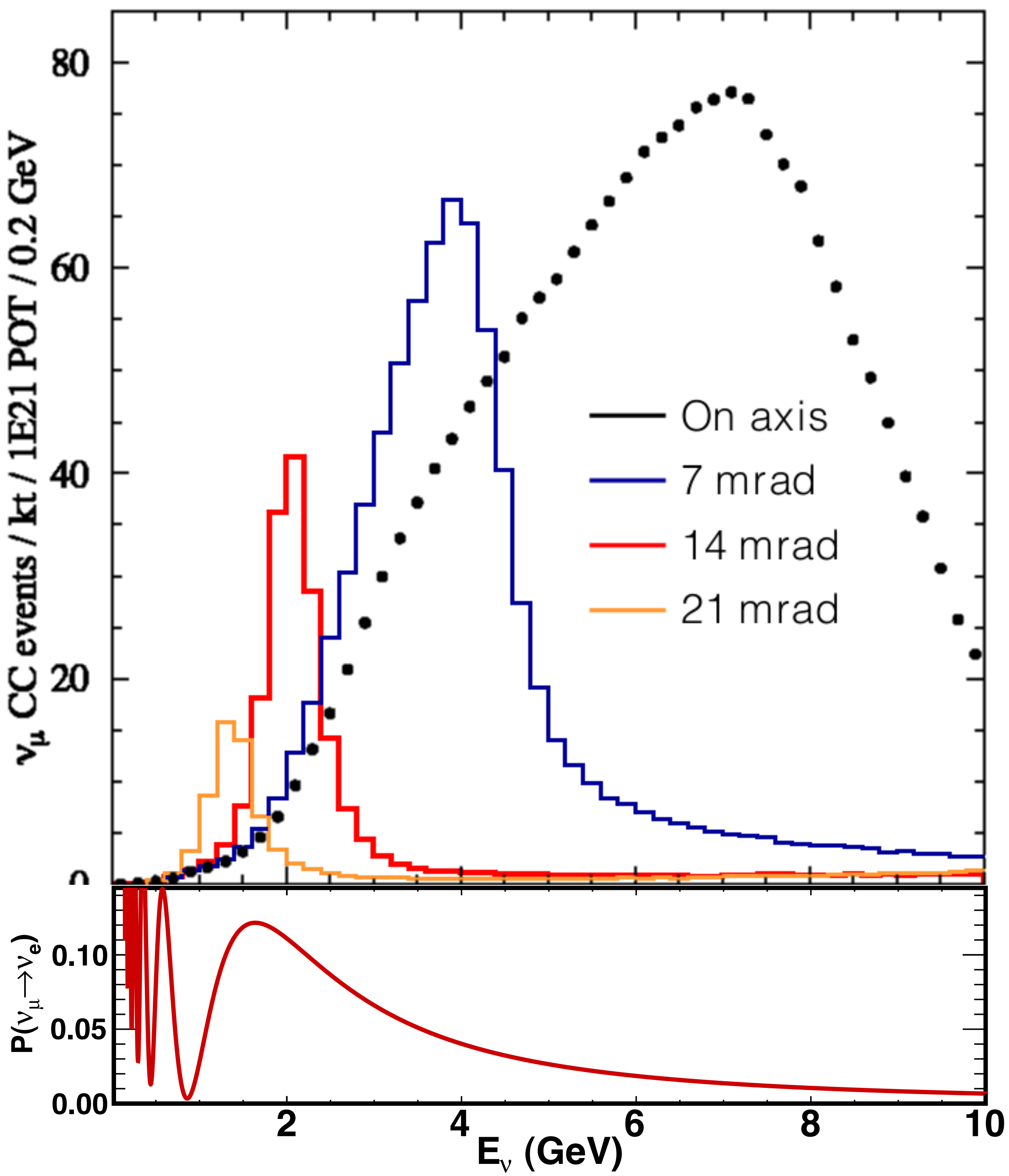
Existing NuMI Beam from FNAL

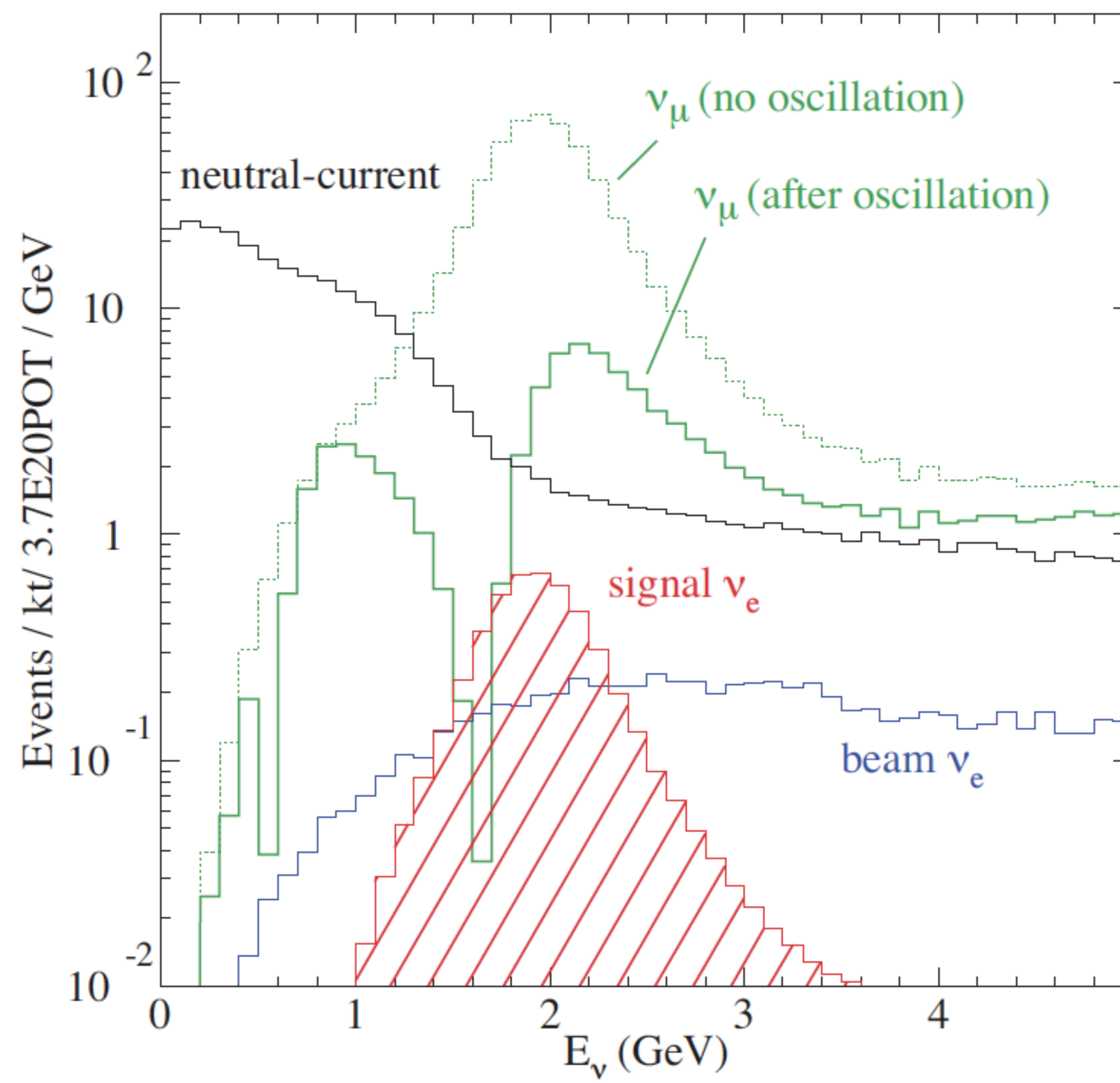
Upgrade from 360 kW to 700 kW in progress

- Goals:
- Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .
- Resolution of the neutrino mass hierarchy
- Search for CP violation in the neutrino sector
- Determine the octant of θ_{23}
- Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.

Nearly identical ~300 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

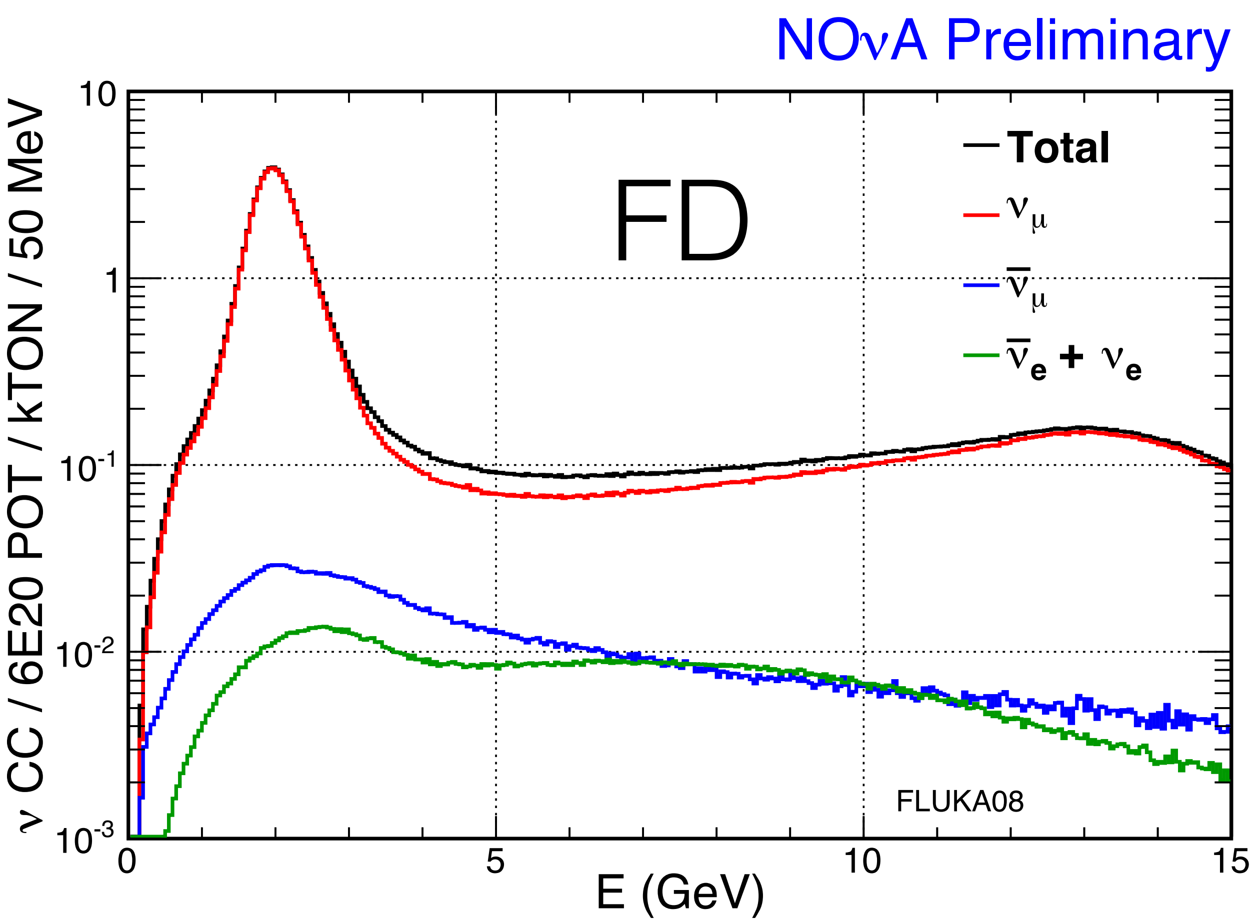
Why Go Off-Axis?

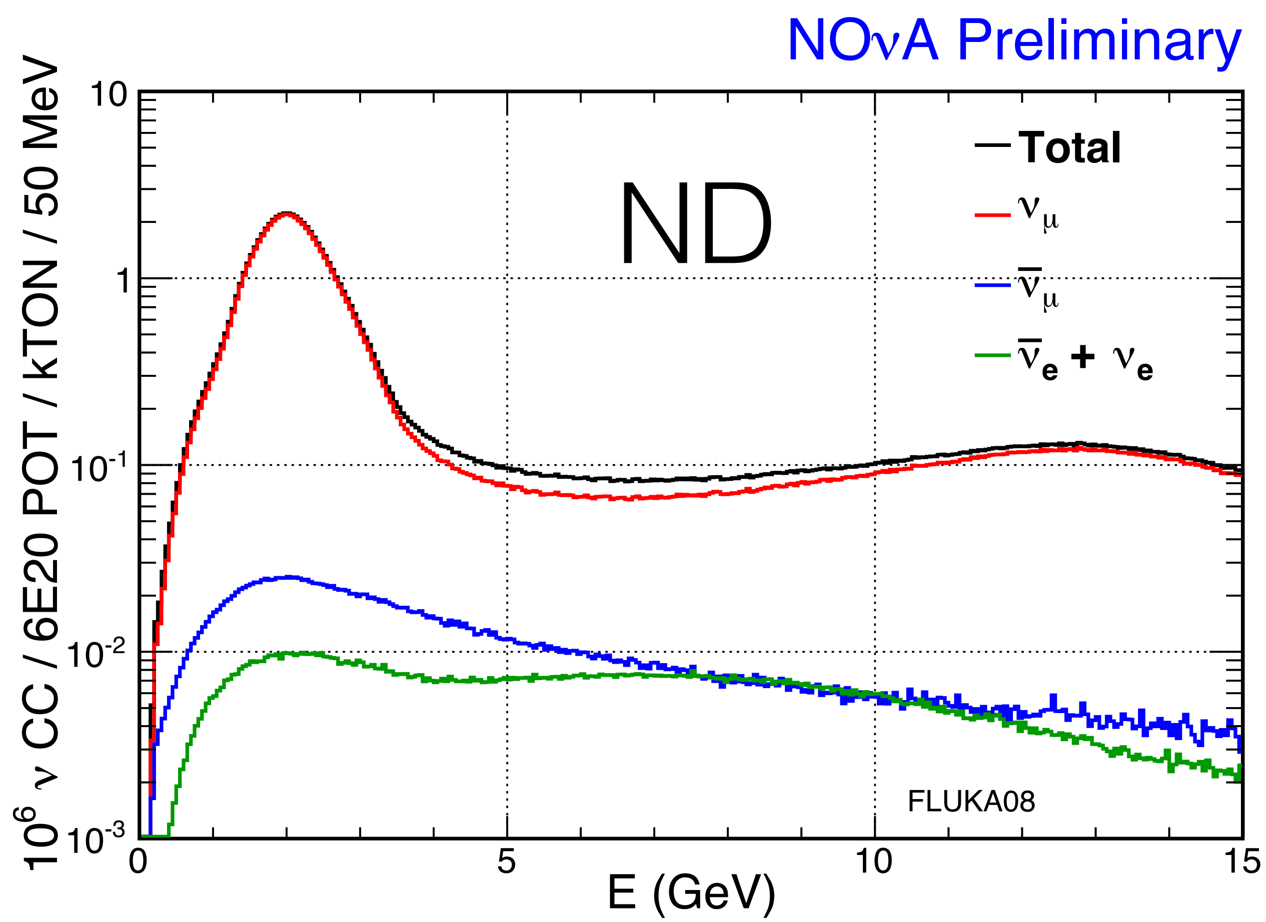




- Narrow-band beam, in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds.

Forward Horn Current Mode





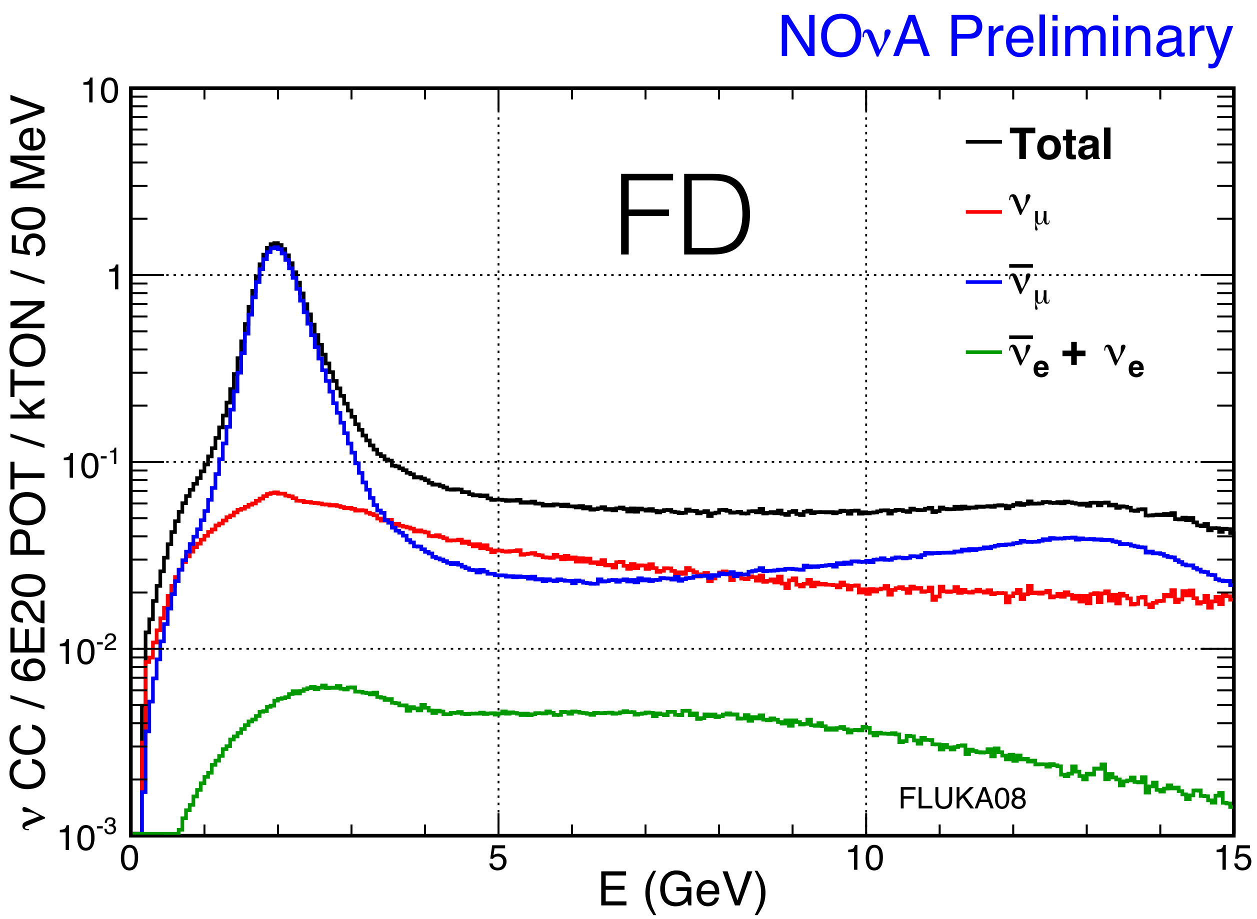
	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

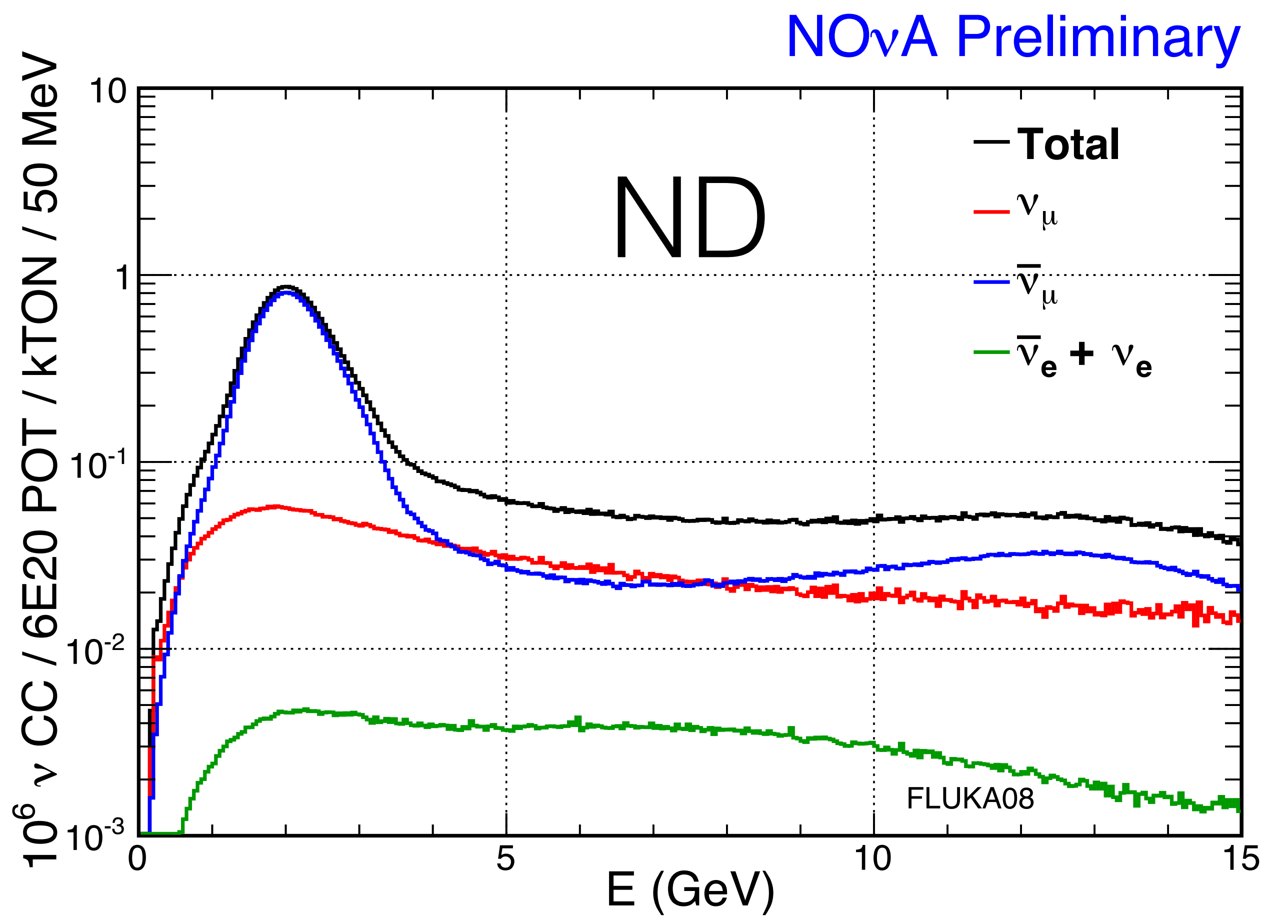
$x10^6$	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.6%

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.7%

Reverse Horn Current Mode





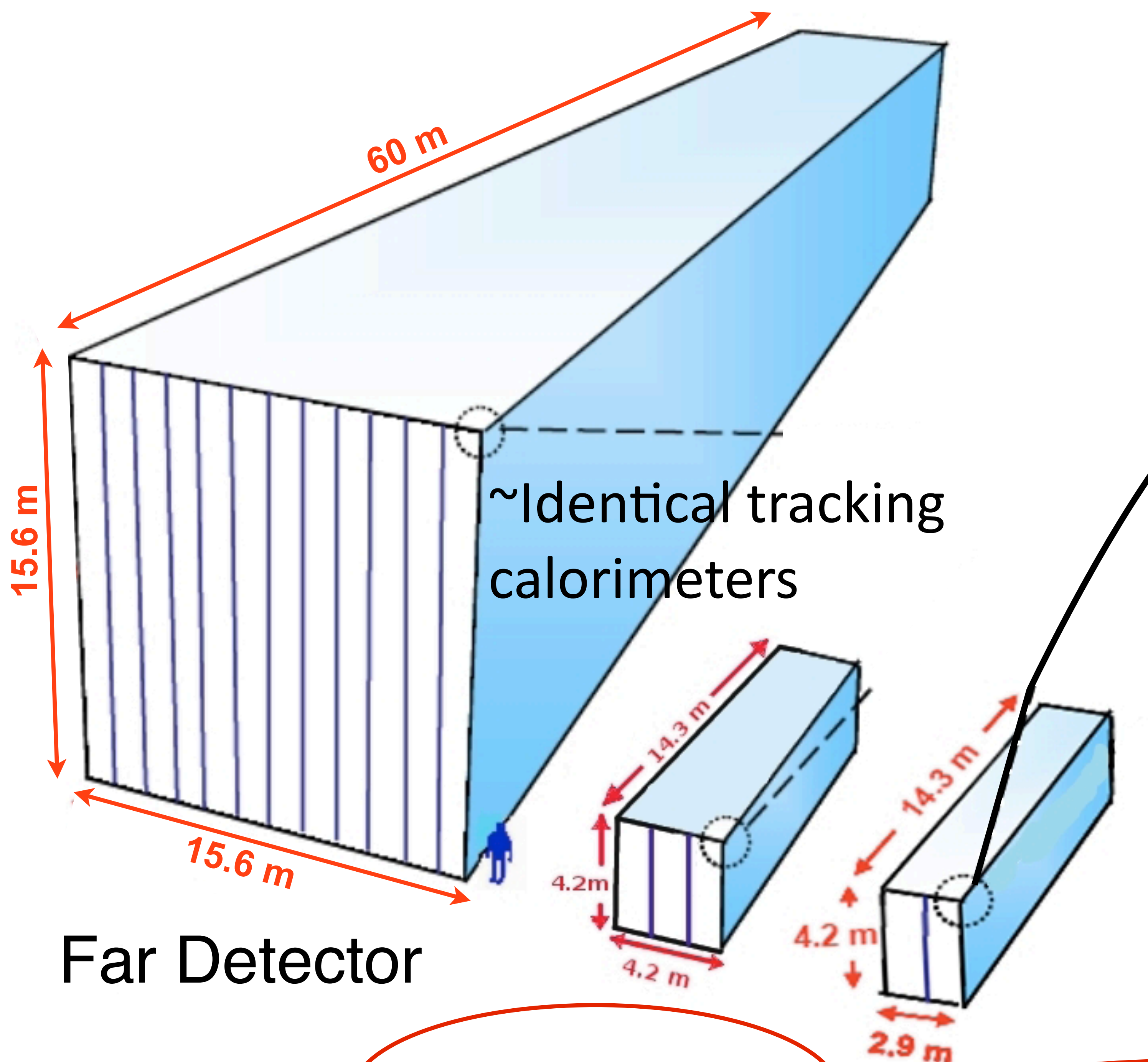
	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

$\times 10^6$	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

[1,3]GeV: $(\nu_e + \overline{\nu}_e)/\nu_\mu$ = 0.8%

[1,3]GeV: $(\nu_e + \overline{\nu}_e)/\nu_\mu$ = 1.0%

The NOνA Detectors

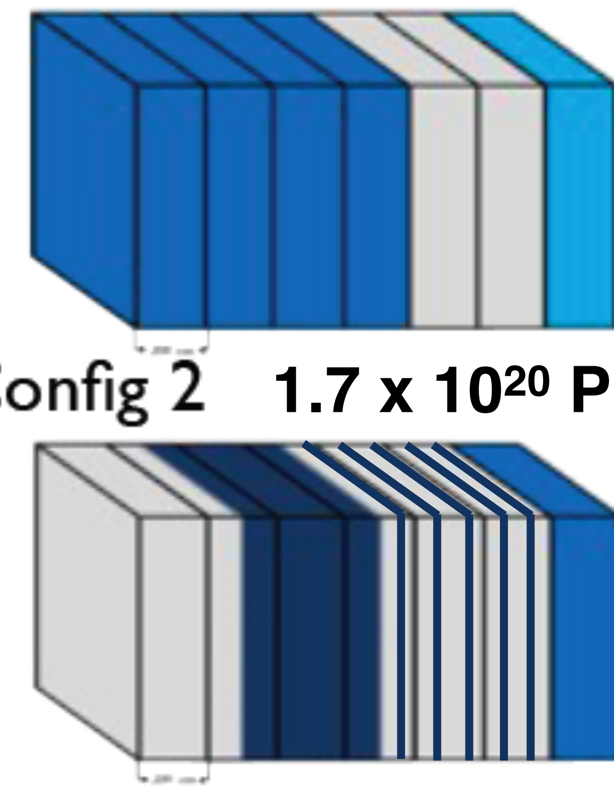


Near Detector

Prototype Near Detector

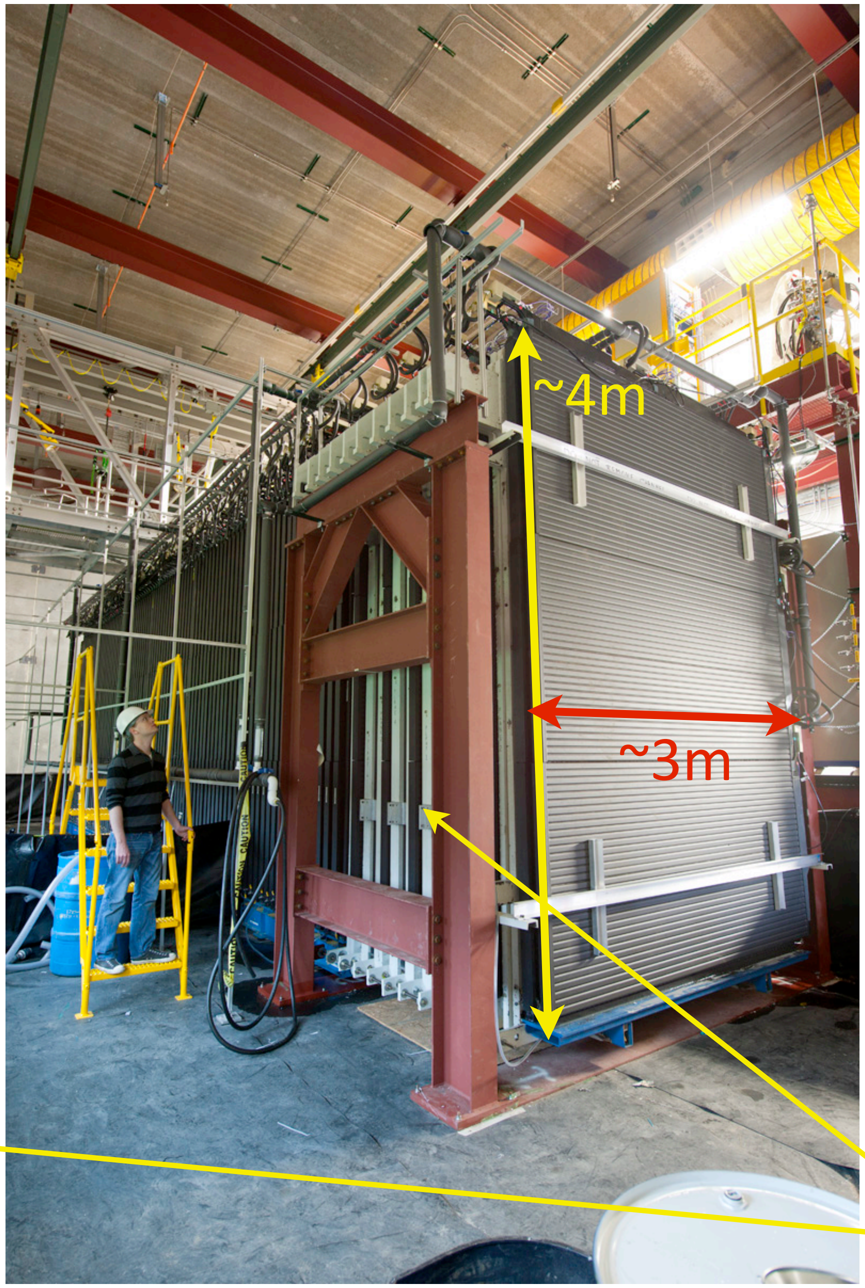
Config 1 **9.6 x 10^{18} POT NuMI**

Config 2 **1.7 x 10^{20} POT NuMI**



- Fully instrumented
- Mostly instrumented
- Partially instrumented
- Uninstrumented

Near Detector On the Surface (NDOS) Prototype

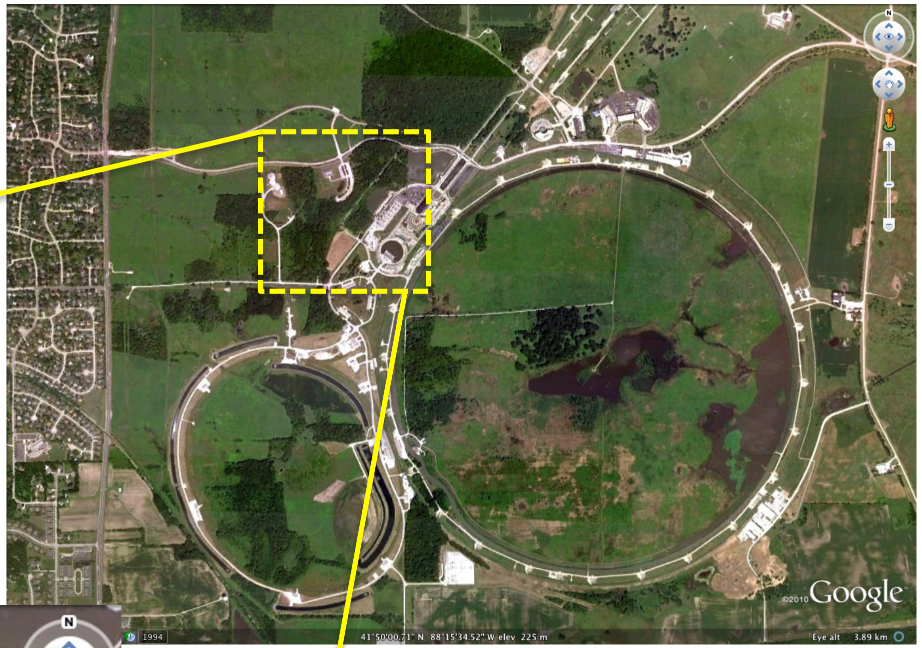


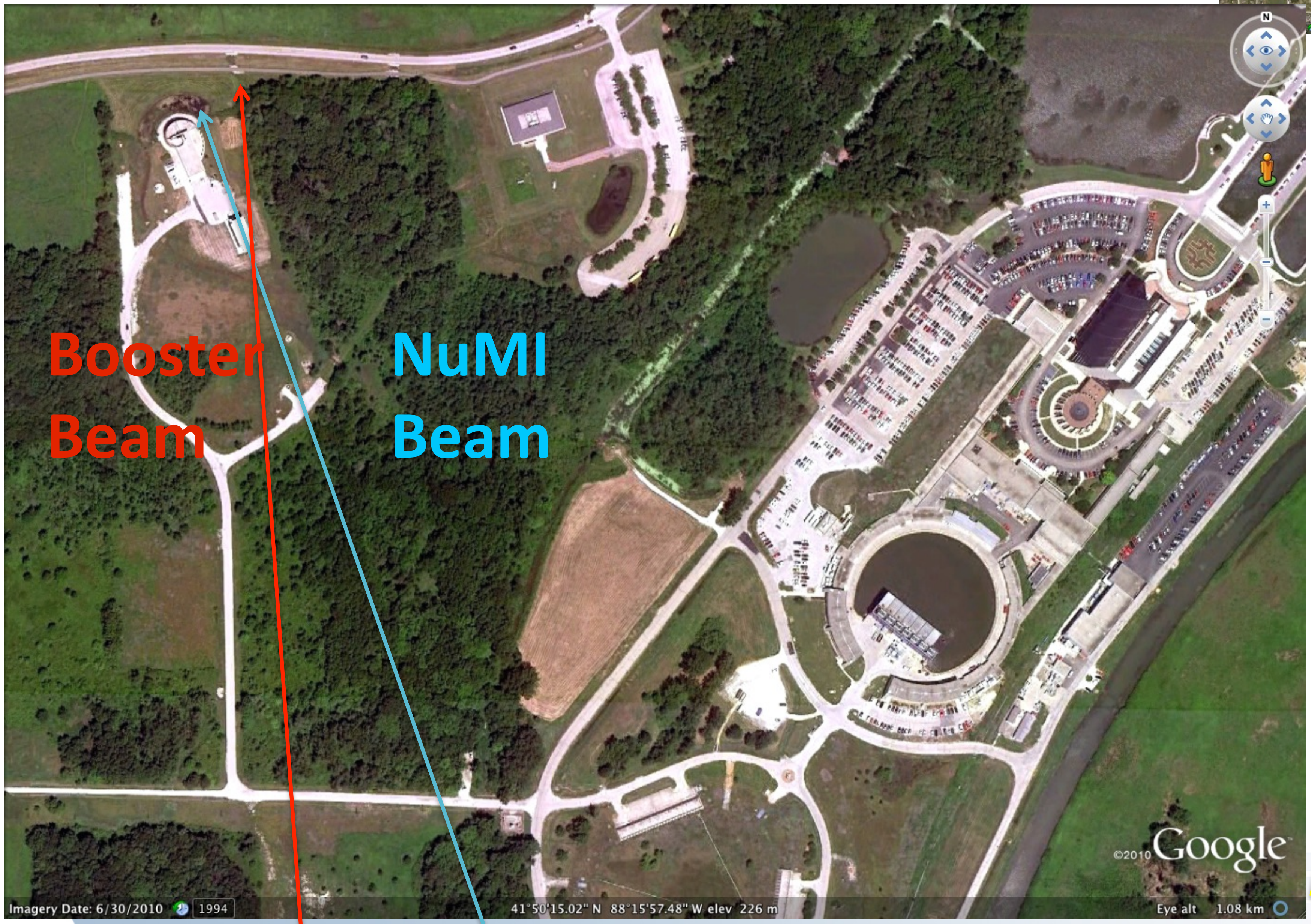
- Designed to test:
  - detector component construction and installation procedures
  - all detector systems end-to-end
  - prior to the beginning of construction and installation of Far Detector.
- 2 modules wide x 3 modules high x 6 blocks long. Far detector is 12 x 12 x 28.
- Muon catcher at end of detector needed to measure energy of muons.

- Installation completed May 9, 2011.
- Commissioning and data collection on-going since 11/2010.

NDOS Beam Exposure

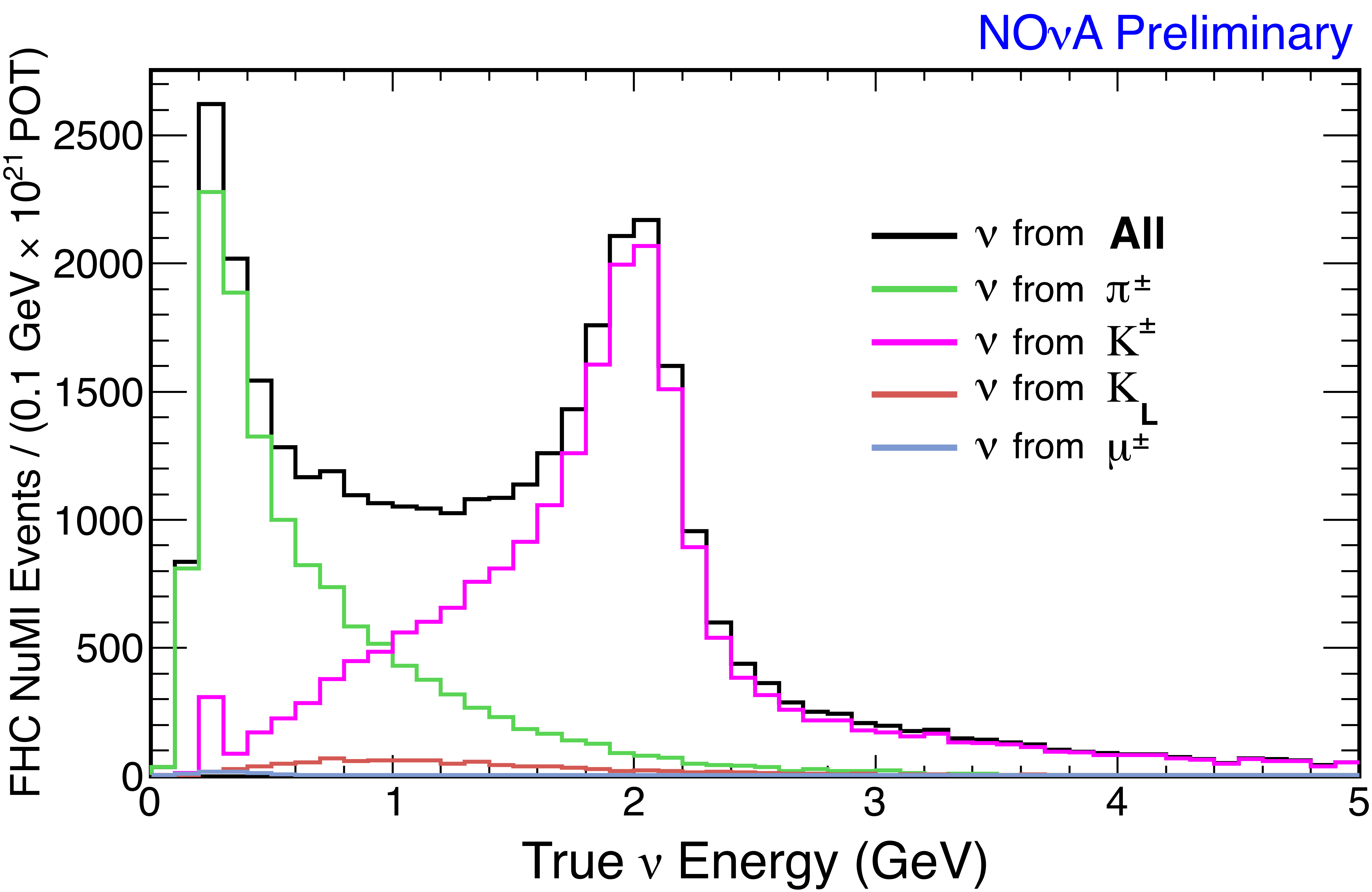
- The NDOS is exposed to BOTH the NuMI and Booster Neutrino beamlines.
- Located ~6.1 degrees off-axis above the NuMI beamline, and along the axis of the Booster beamline.



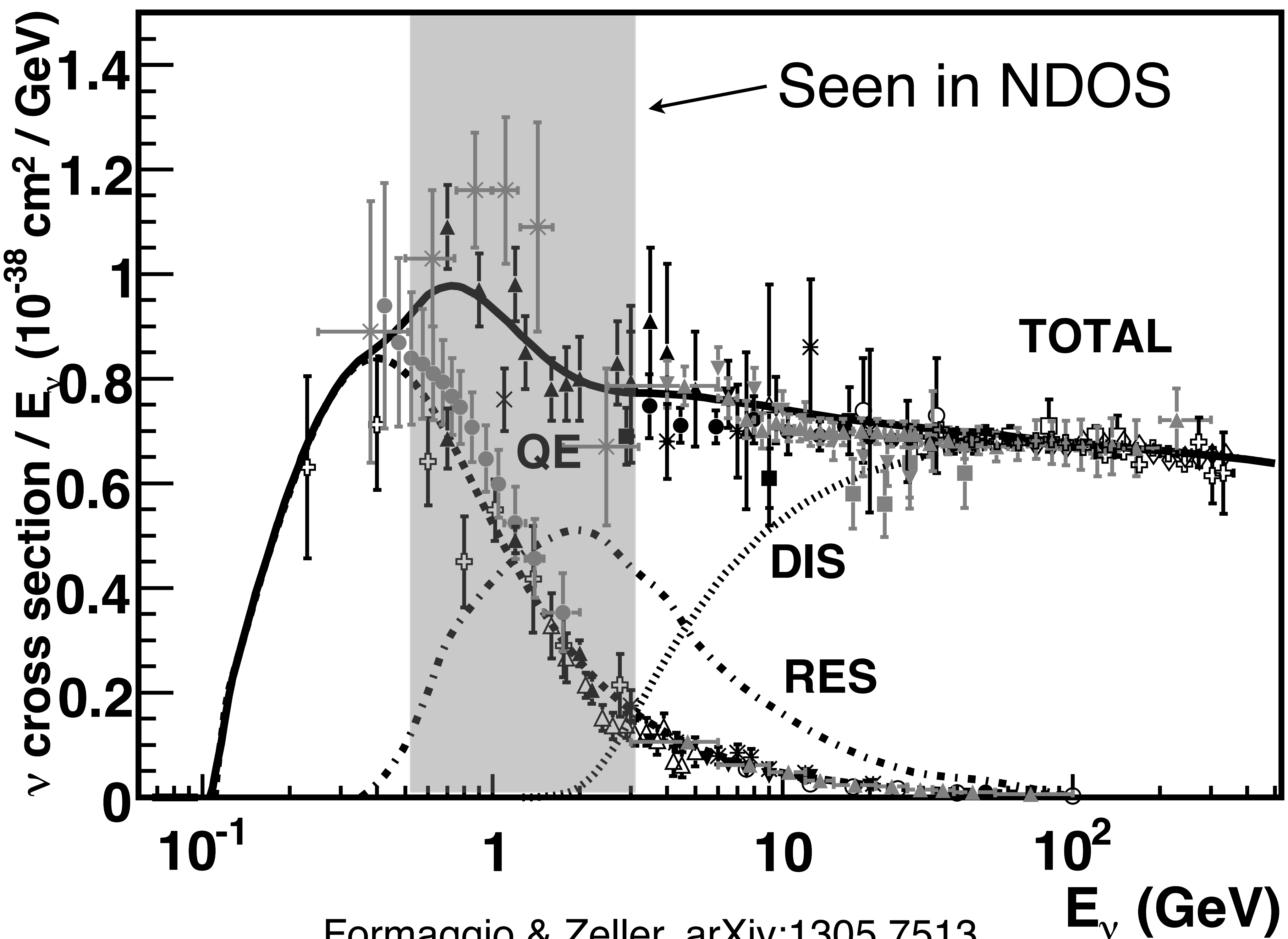


- The longitudinal axis of the detector is aligned with the NuMI beam, but rotated ~21.5 degrees with respect to the Booster beamline.

NuMI Beam Spectrum in NDOS

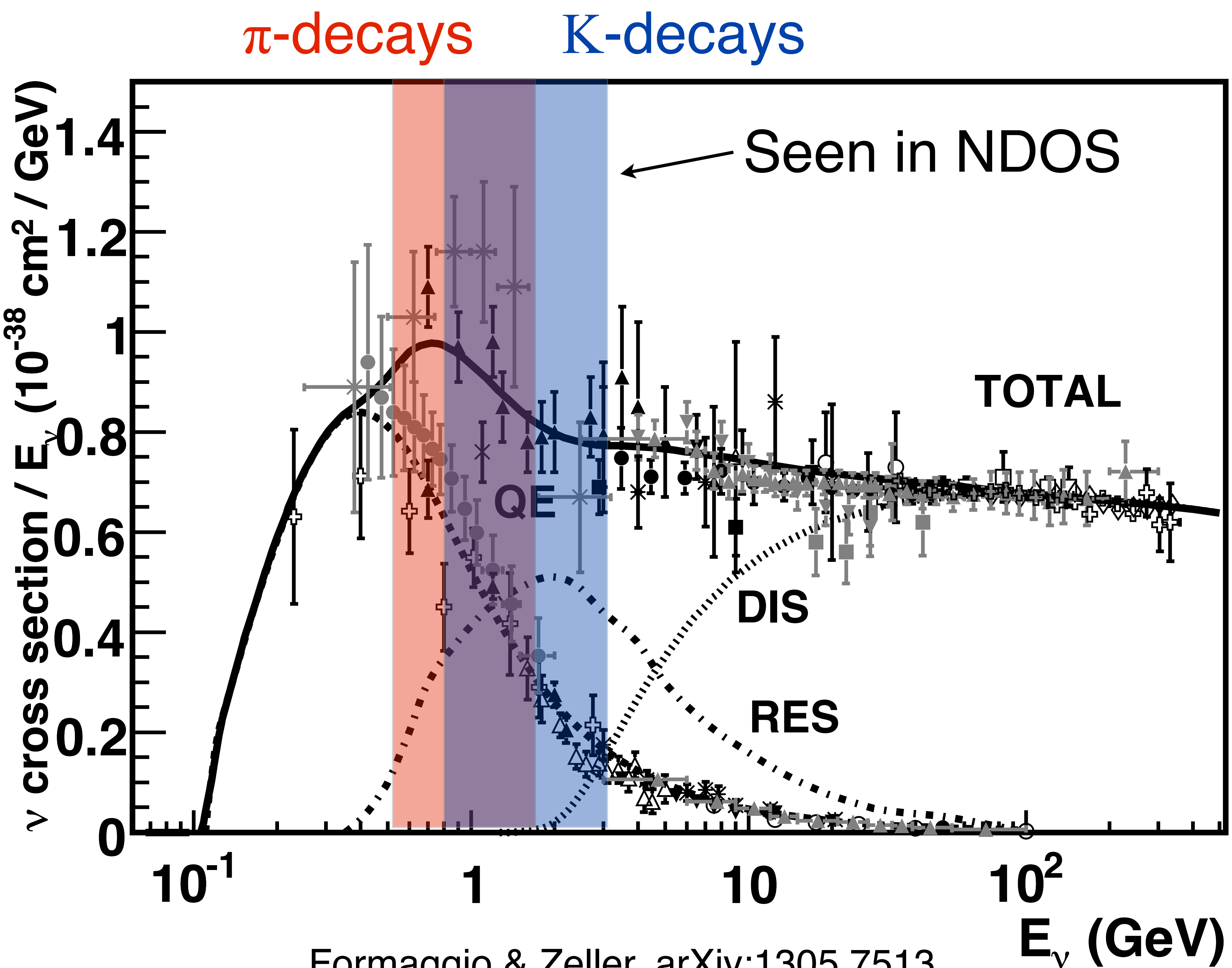


NDOS Cross Section Measurements



Formaggio & Zeller, arXiv:1305.7513

NDOS Cross Section Measurements



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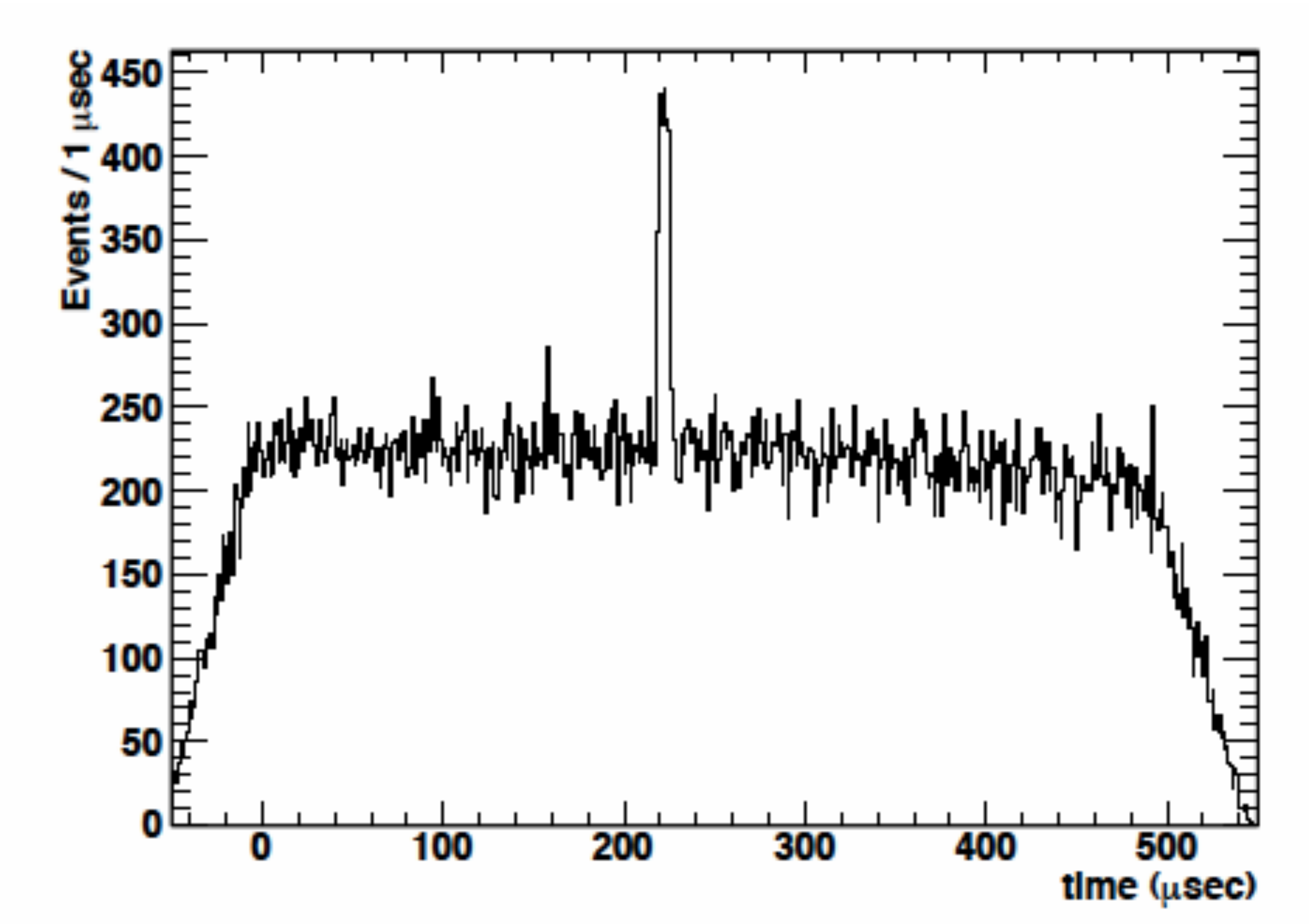
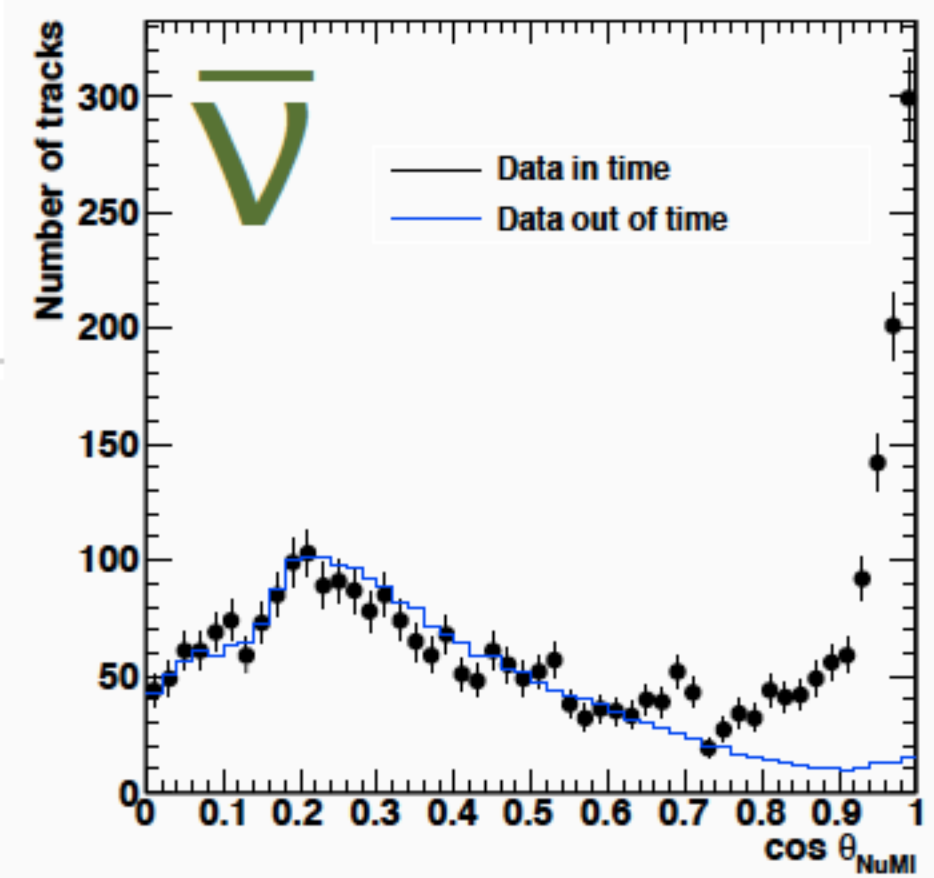
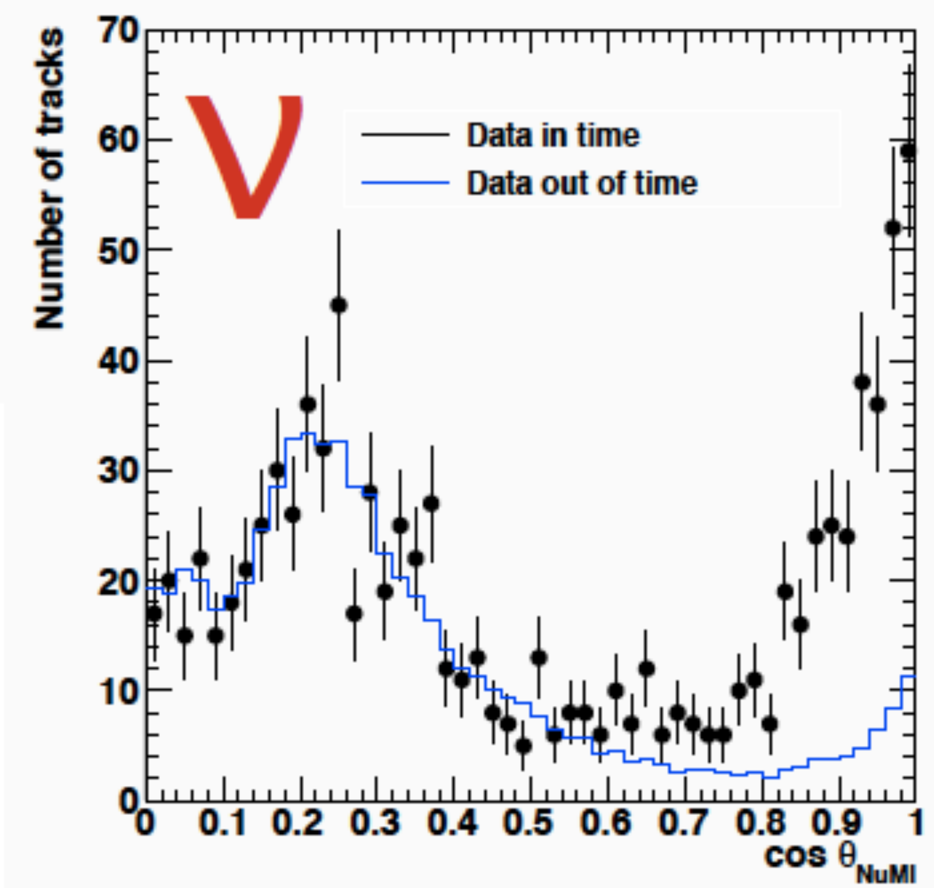
Finding NuMI Events in NDOS

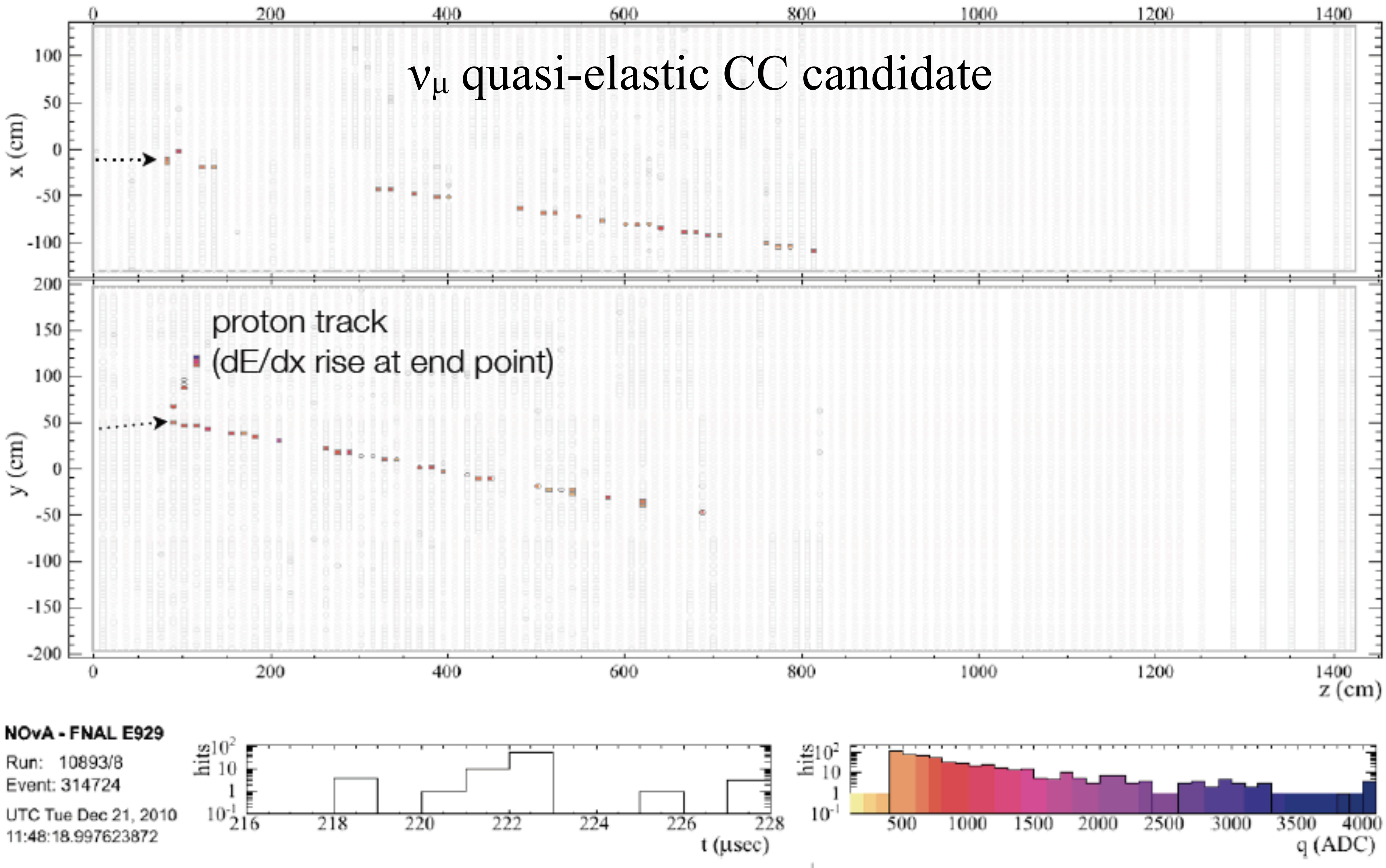




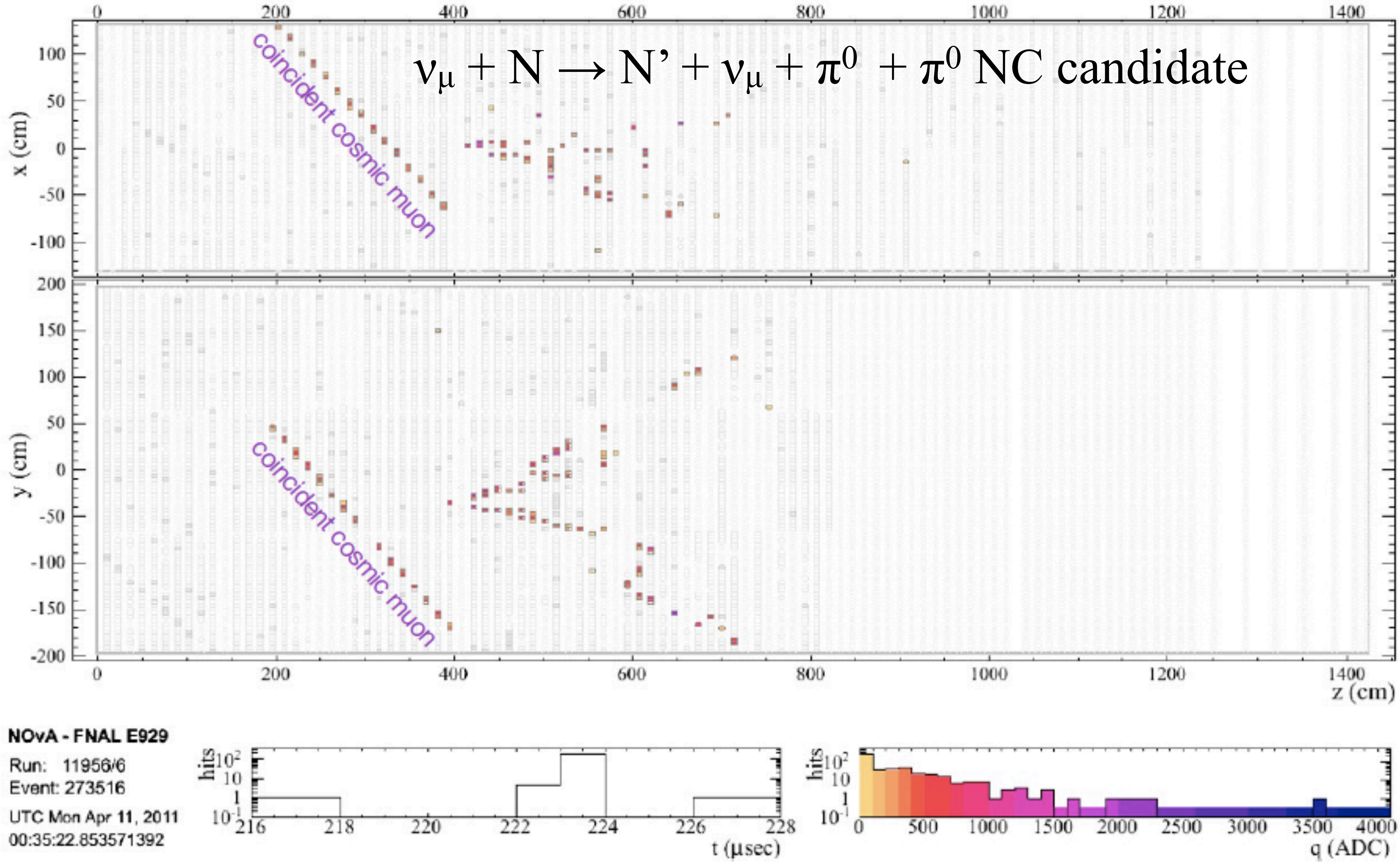


- Clear peak in timing distribution at expected position within trigger time window.
- Clear excess of reconstructed tracks along beam direction.

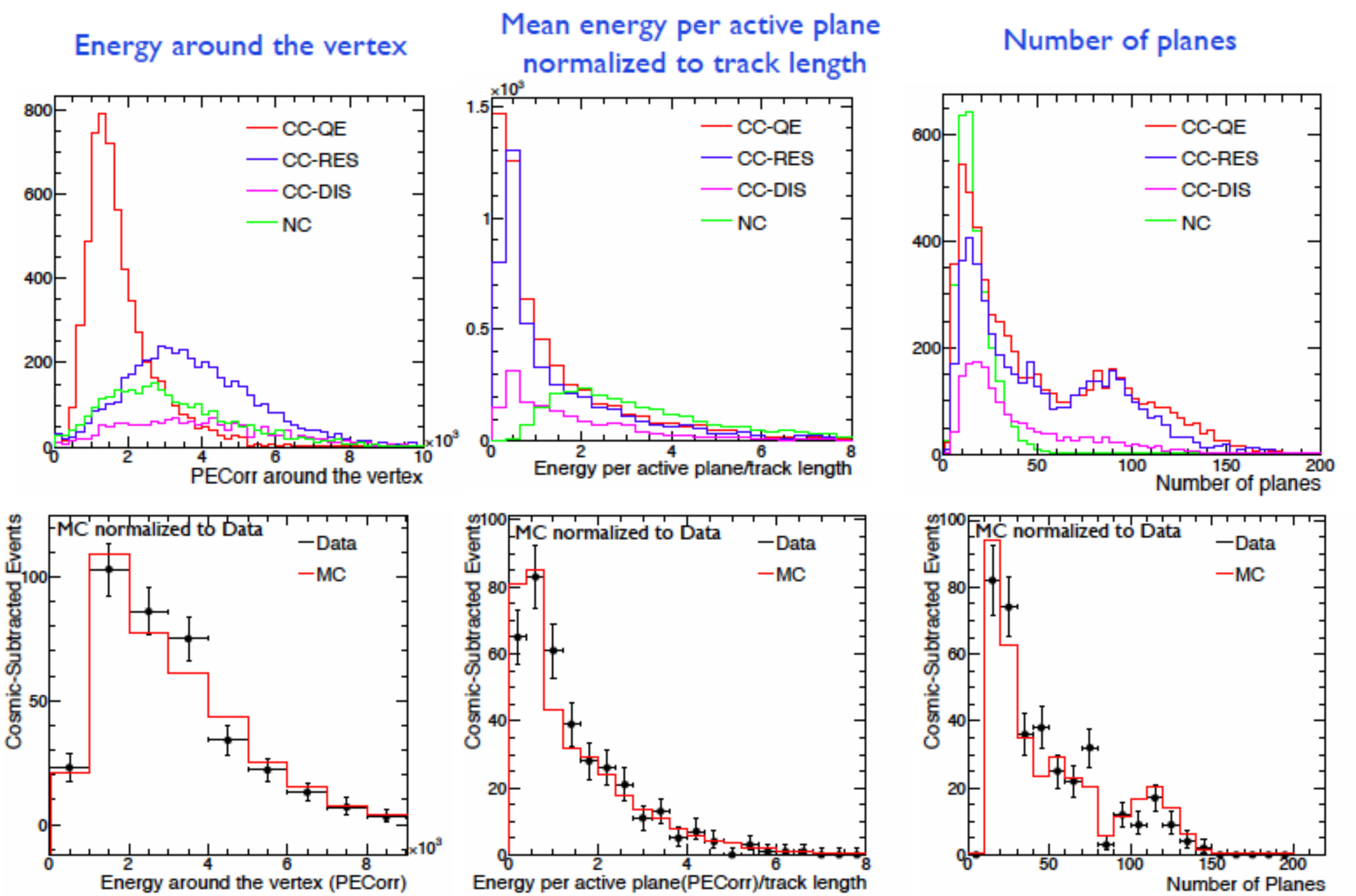
NuMI Events in NDOS



NuMI Events in NDOS

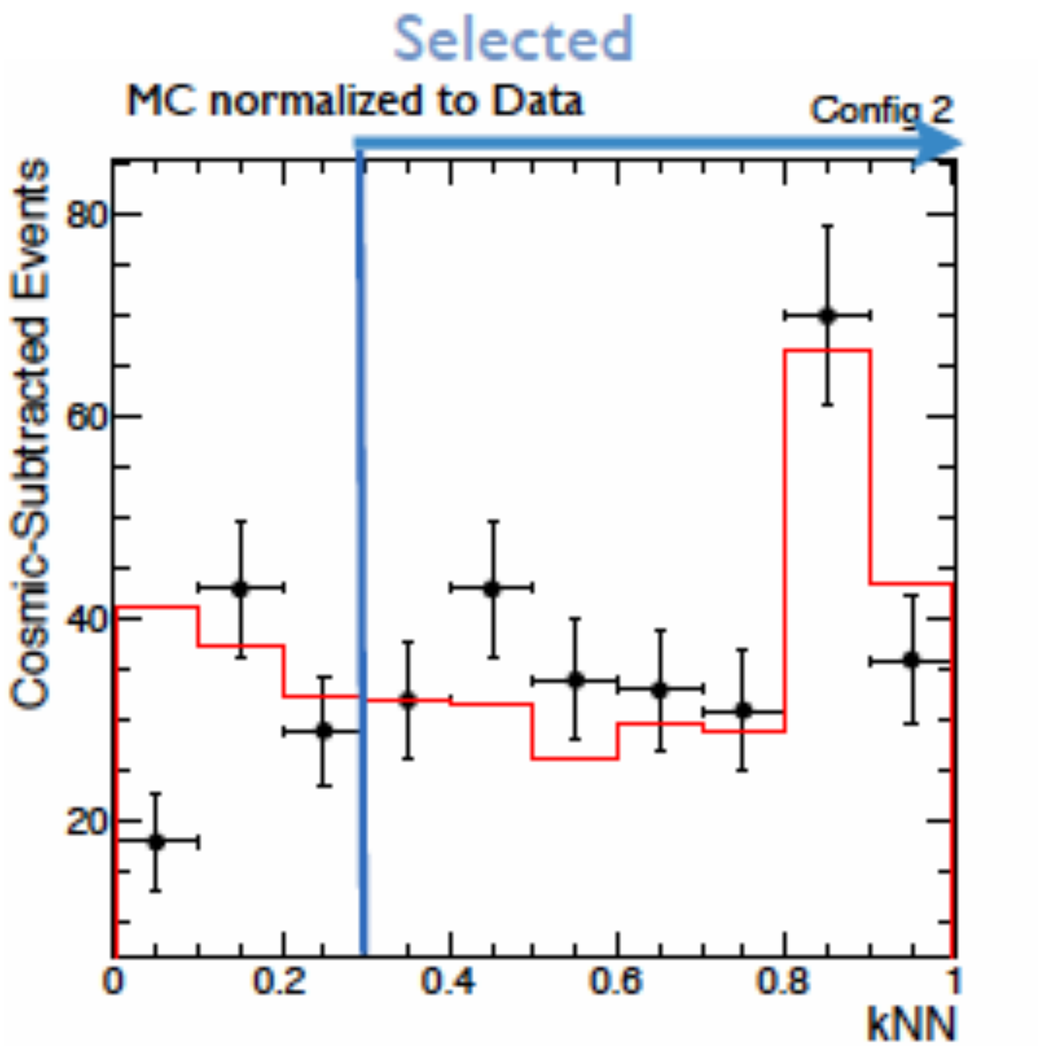


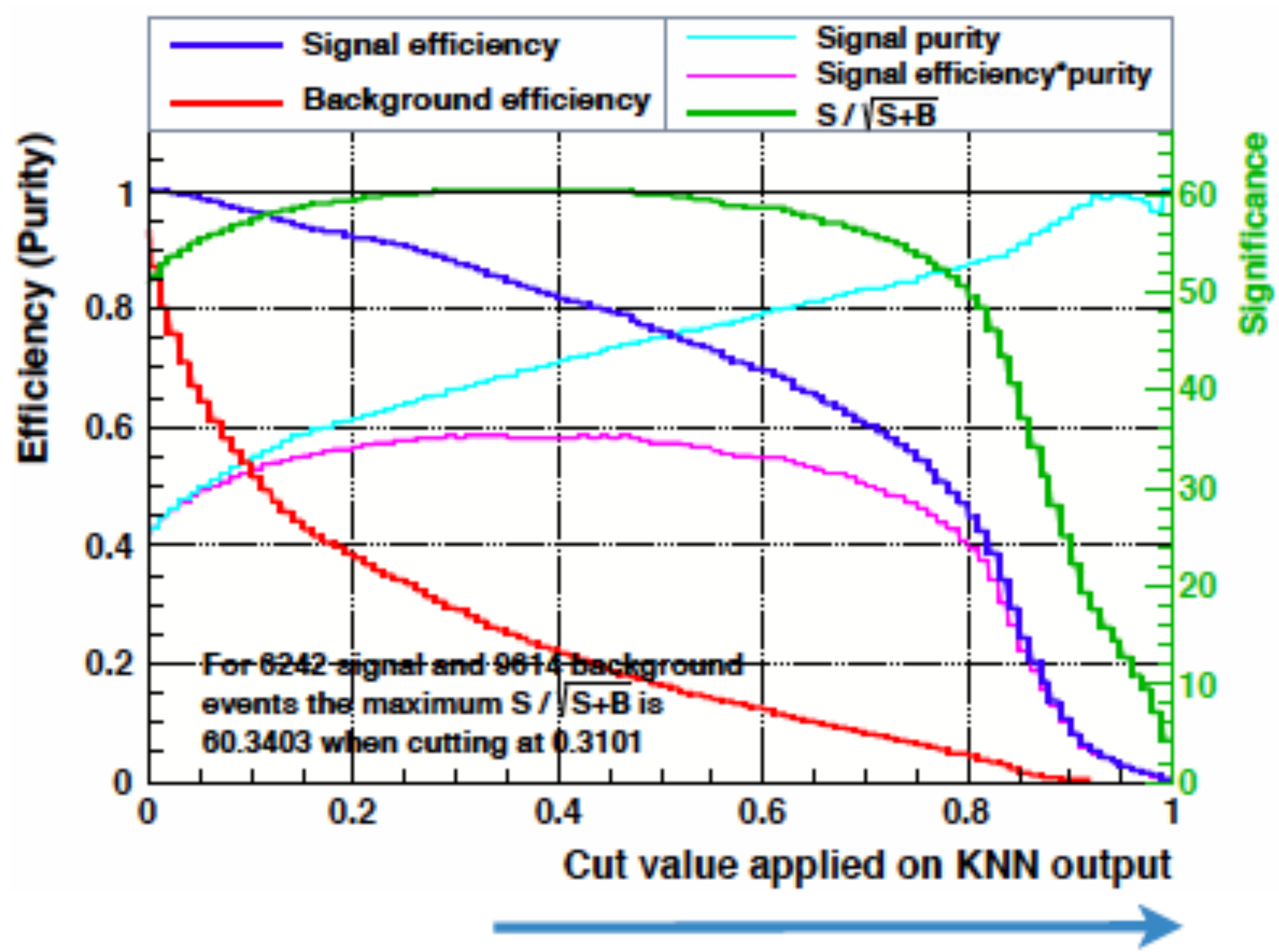
Measurement of ν_μ CC *QE* Cross-Section in NDOS (Minerba Betancourt, first NOvA Ph.D.!)



- Multivariate analysis based on reconstructed quantities used to separate QE from non-QE and NC events
- Shapes of MC distributions agree well with data

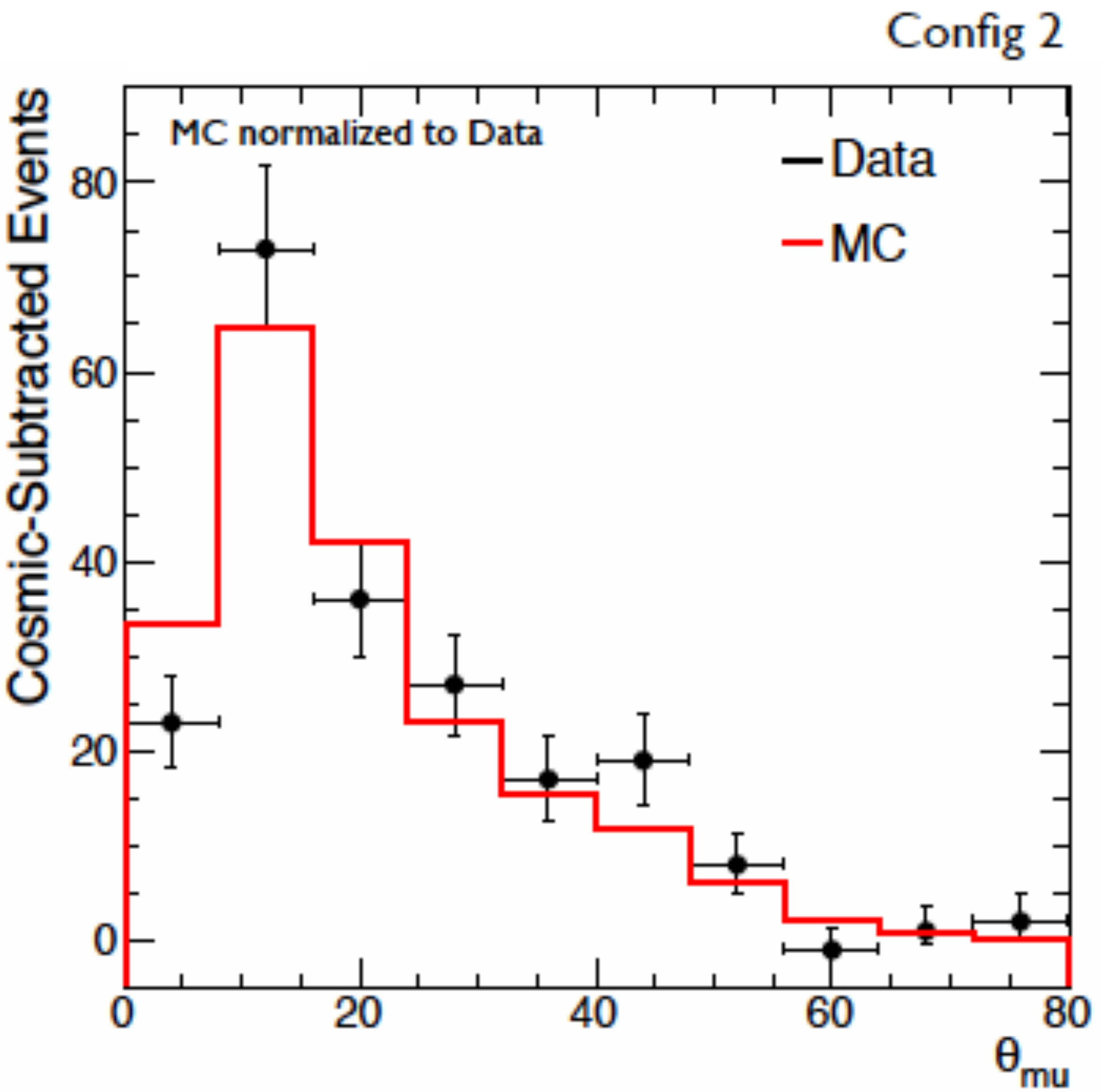
Measurement of ν_μ CC QE Cross-Section in NDOS

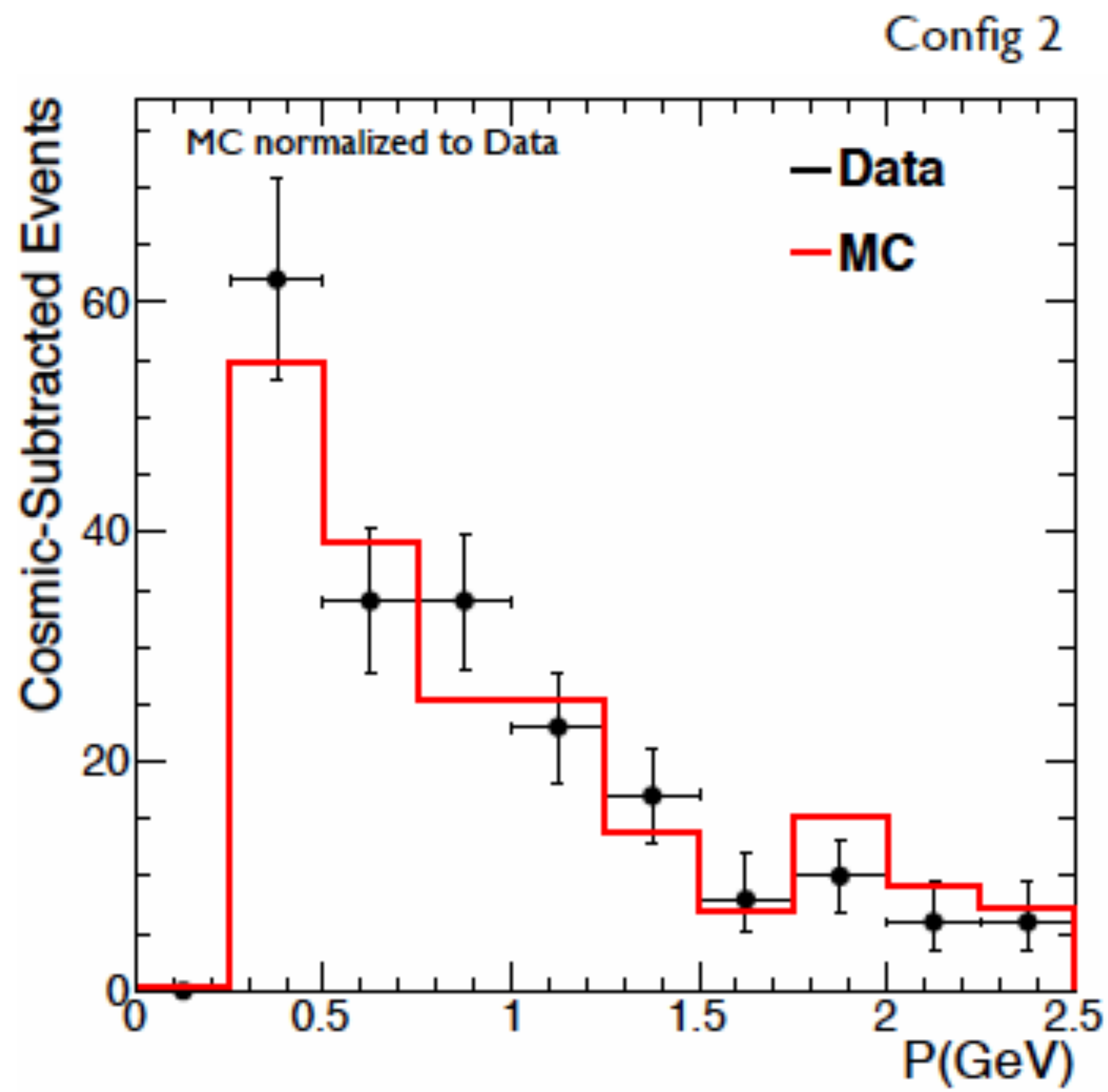




Events selected giving 65% purity and 85% efficiency

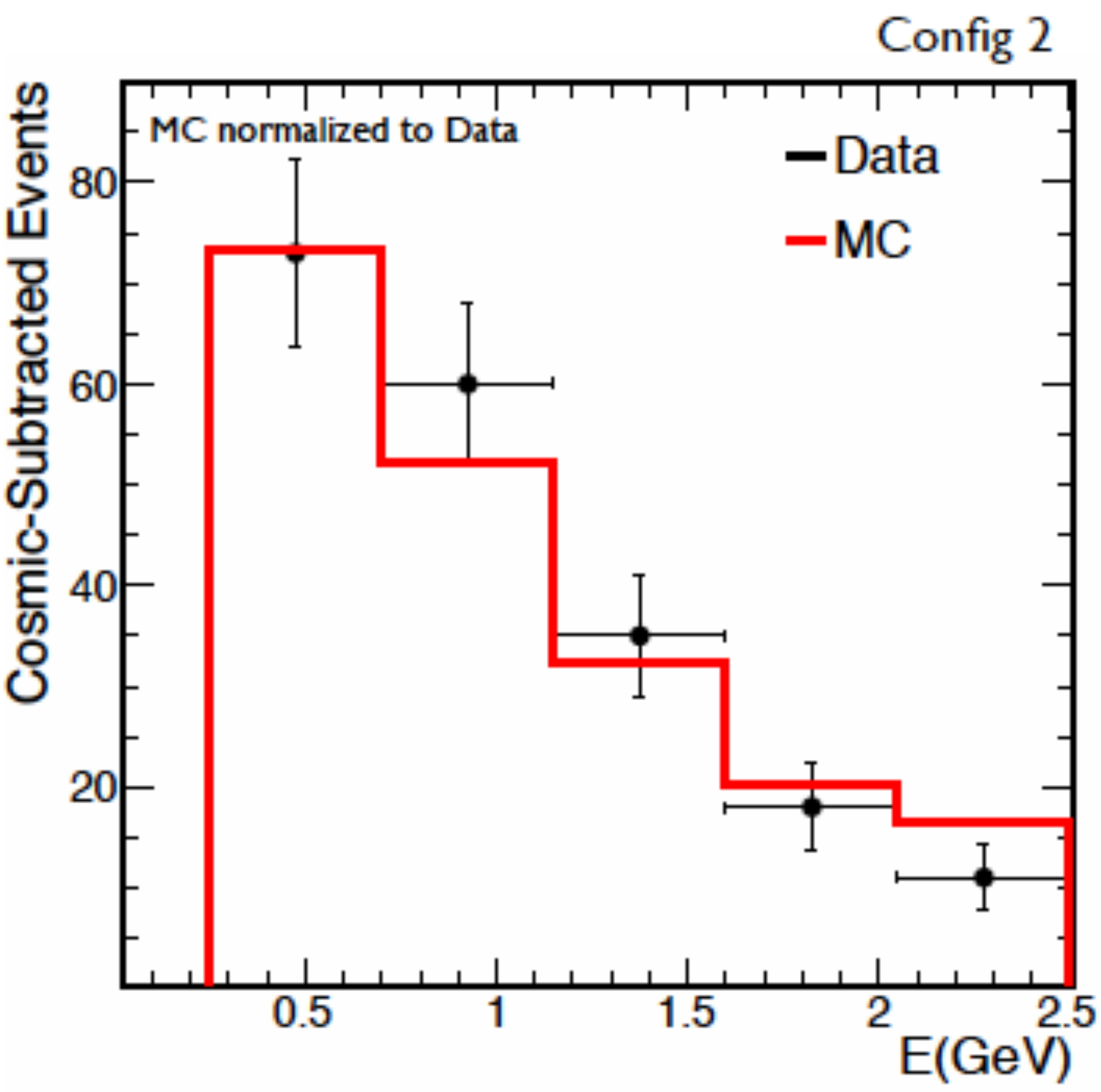
Measurement of ν_μ CC QE Cross-Section in NDOS

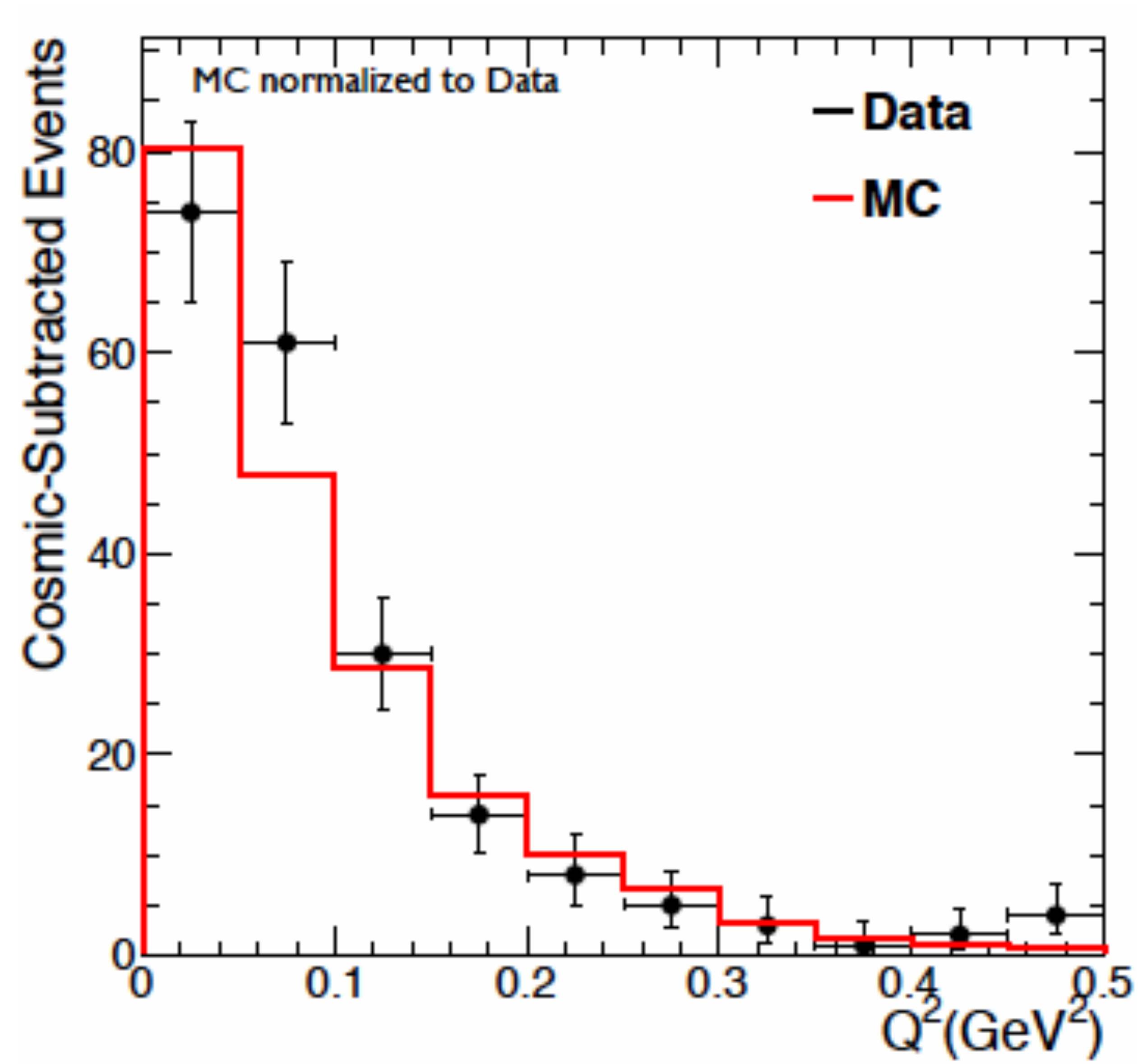




Angle and momentum for ν_μ CC QE selected events after cosmic background subtraction.

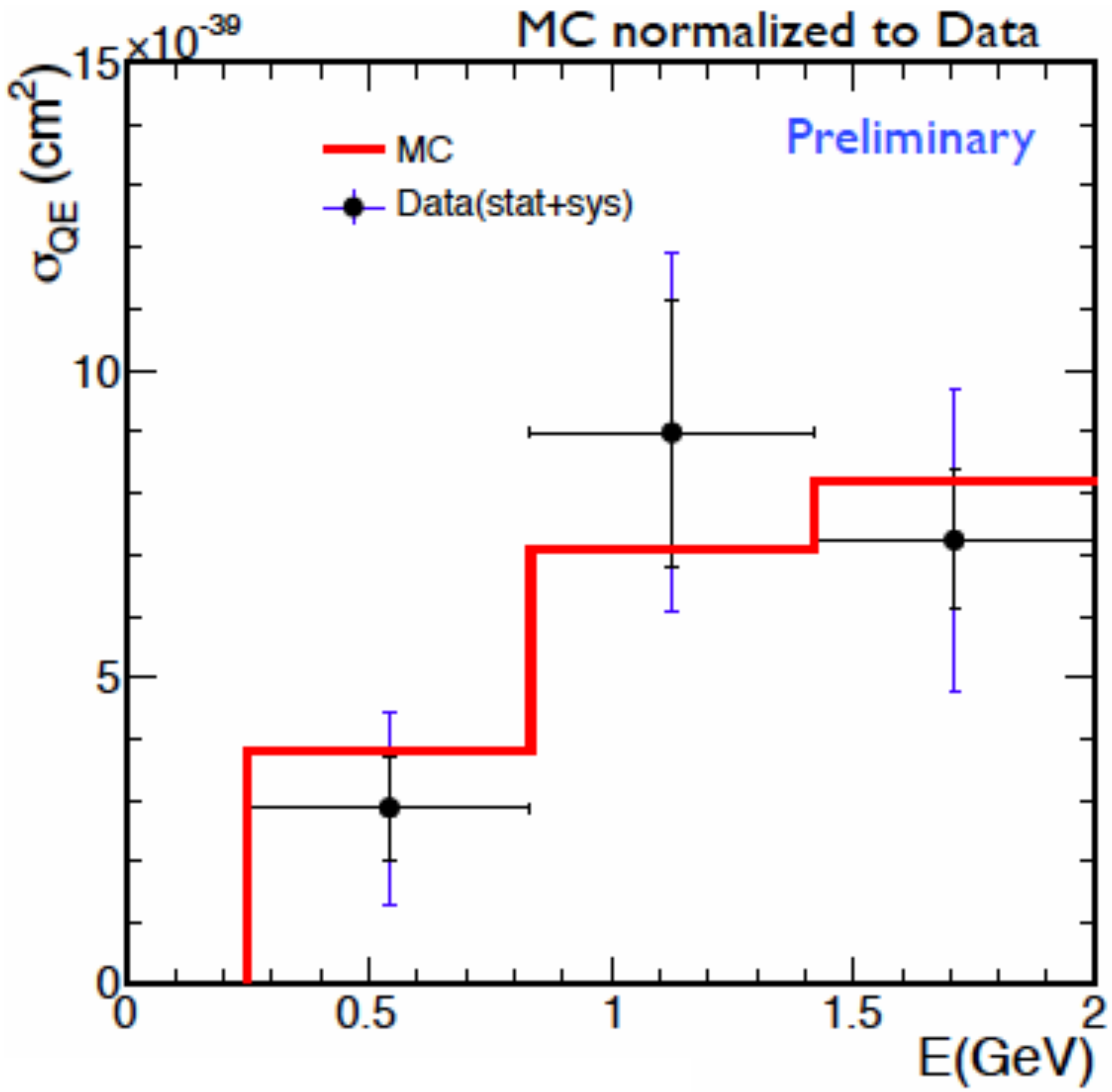
Measurement of ν_μ CC QE Cross-Section in NDOS

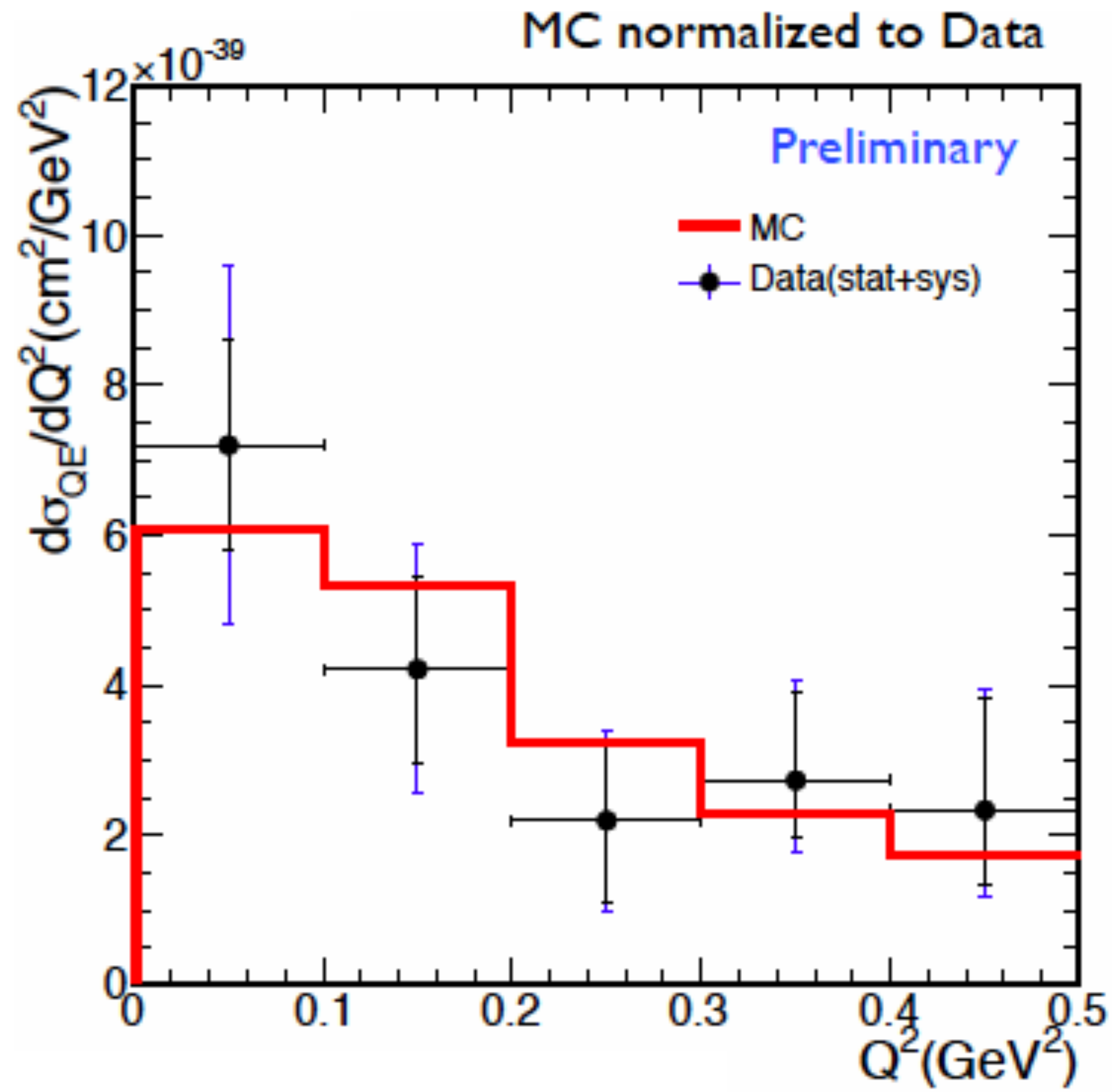




Energy and four-momentum transfer for ν_μ CC QE selected events after cosmic background subtraction.

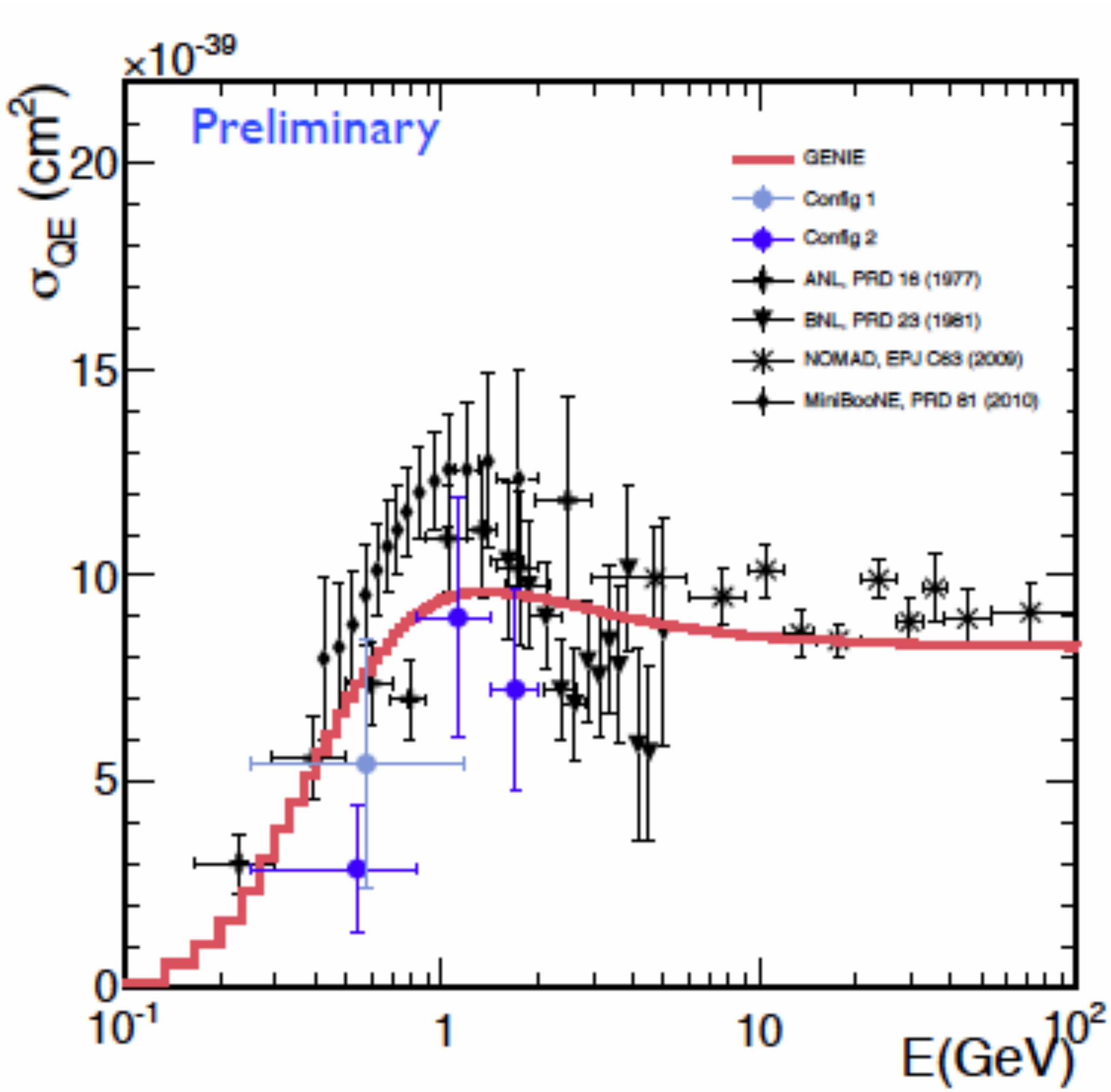
Measurement of ν_μ CC QE Cross-Section in NDOS

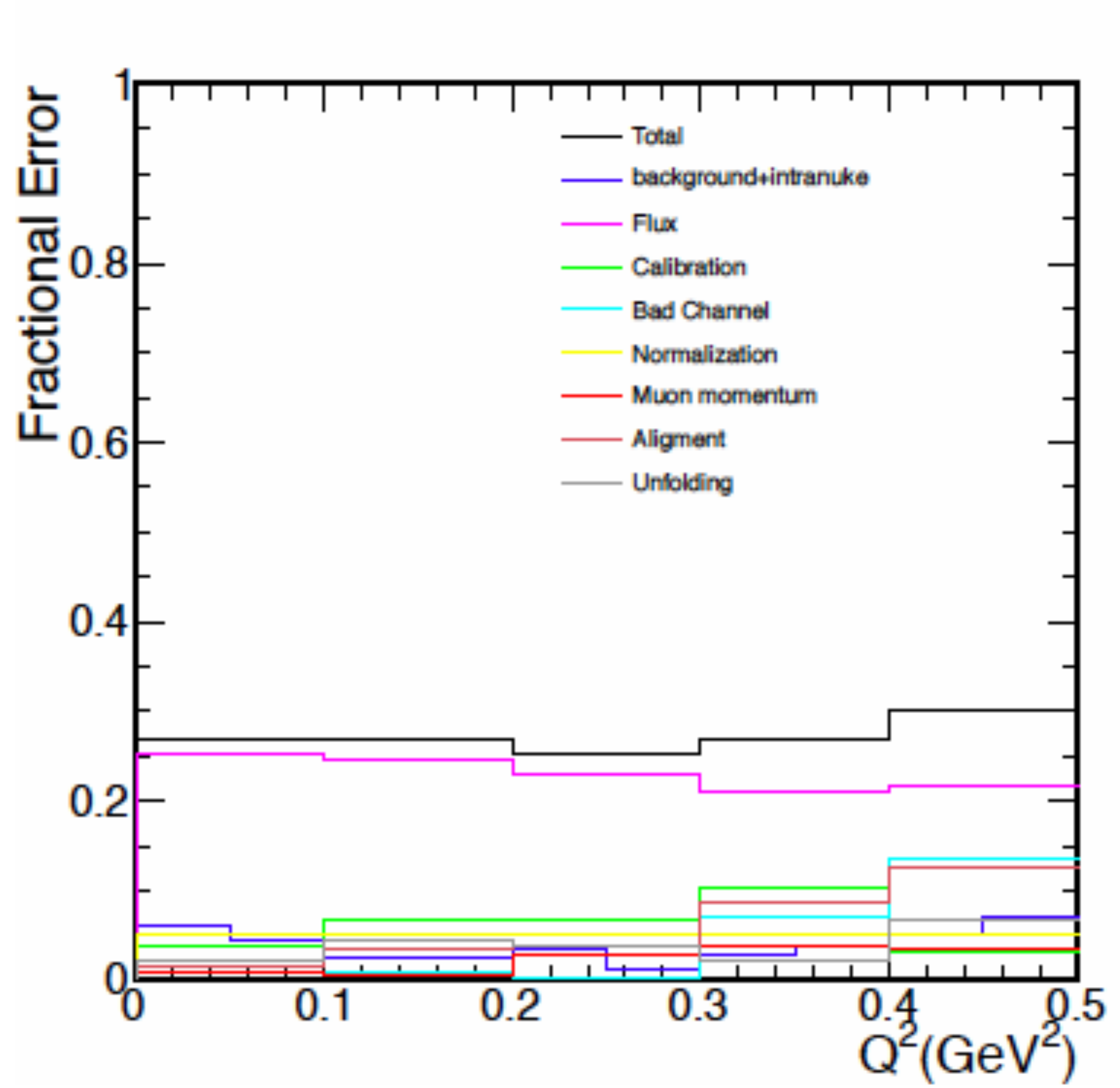




Distributions are unfolded (reco → true), efficiency corrections applied. MC distributions above are normalized to Data.

Measurement of ν_μ CC QE Cross-Section in NDOS

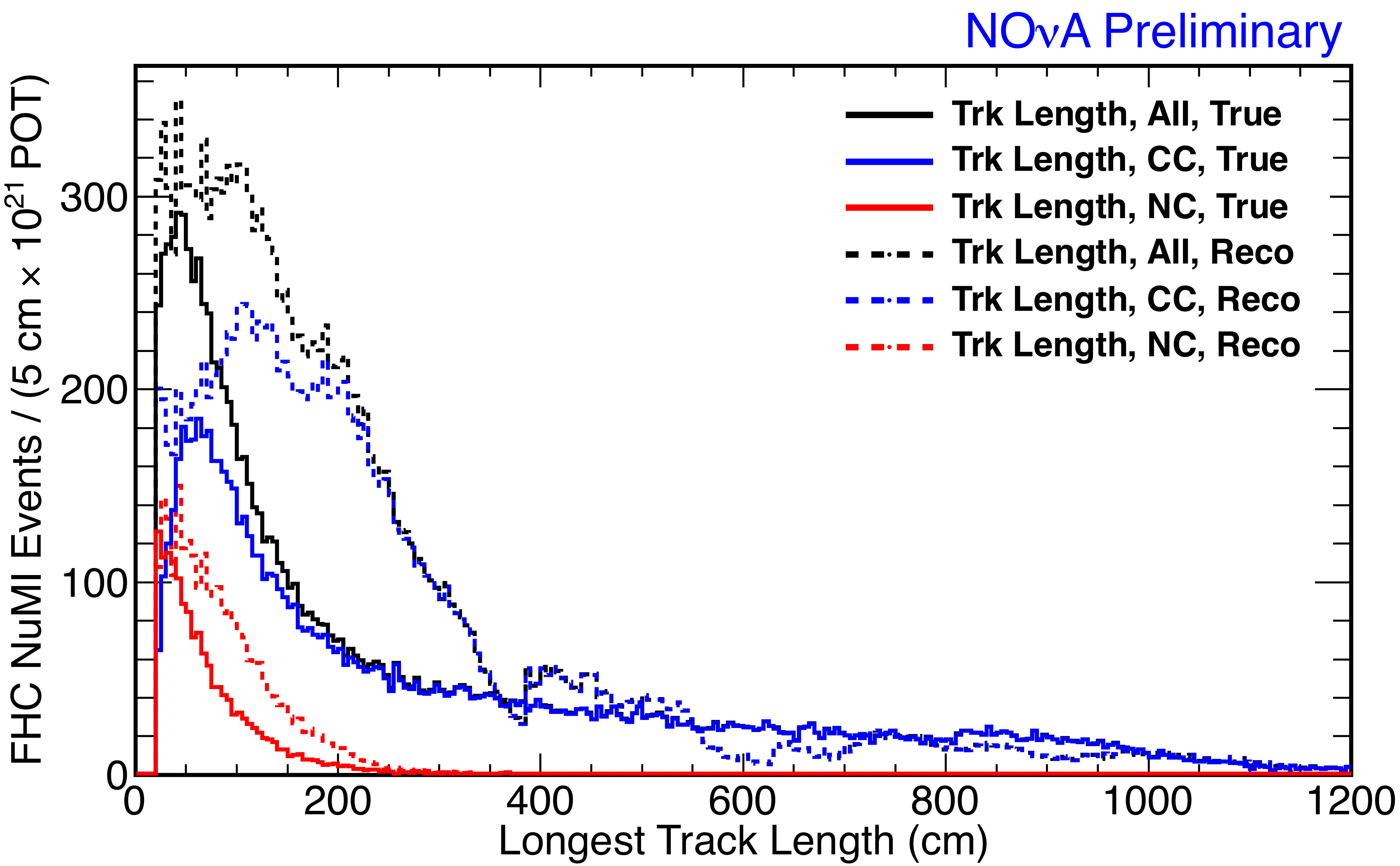




Normalizing by predicted flux shows reasonable agreement to previous measurements for higher values of energy, but the flux prediction is still under investigation.

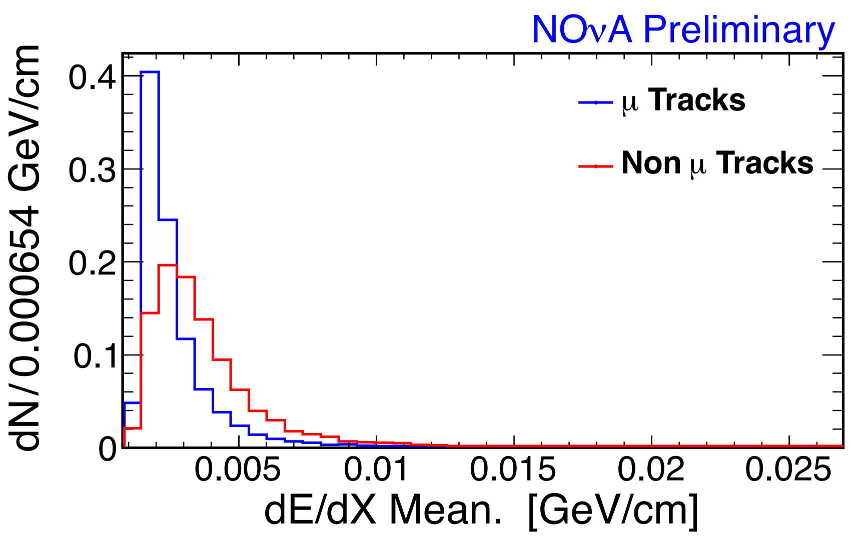
The ~25% uncertainty on the flux shown above is determined by comparing two MC simulations (Fluka to GEANT4).

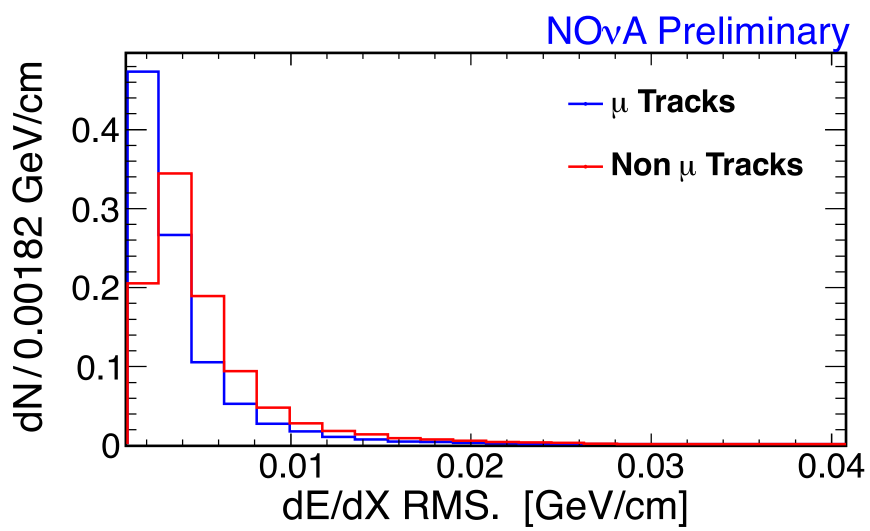
Measurement of ν_μ CC *Inclusive* Cross-Section in NDOS (Enrique Arrieta Diaz)

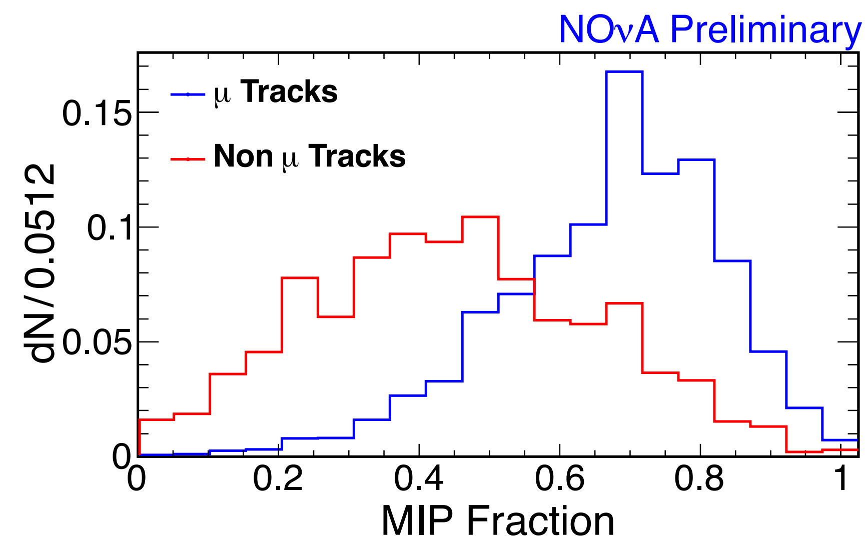


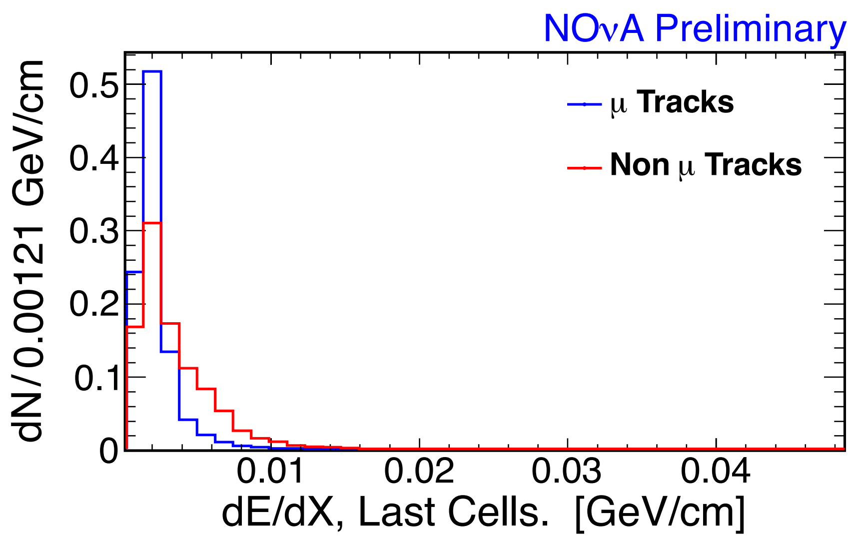
Events with tracks longer than 2m long are from ν_μ CC interactions

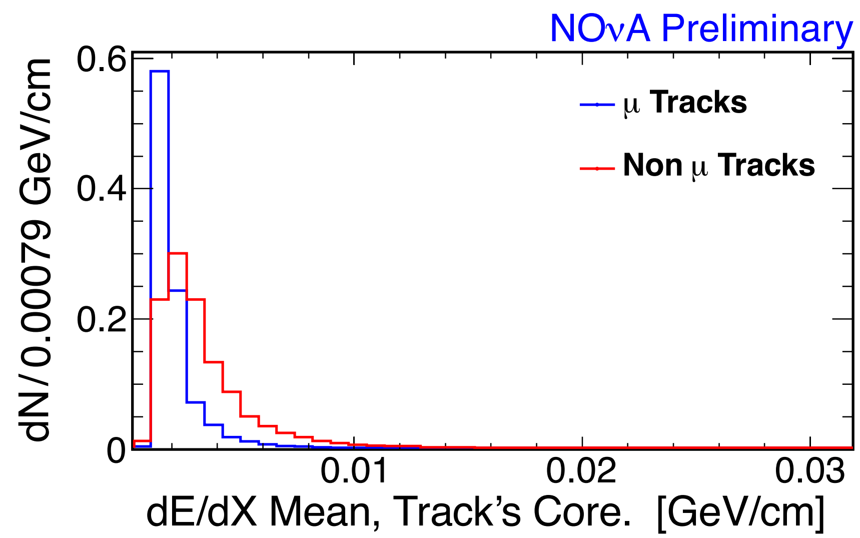
Measurement of ν_μ CC Inclusive Cross-Section in NDOS





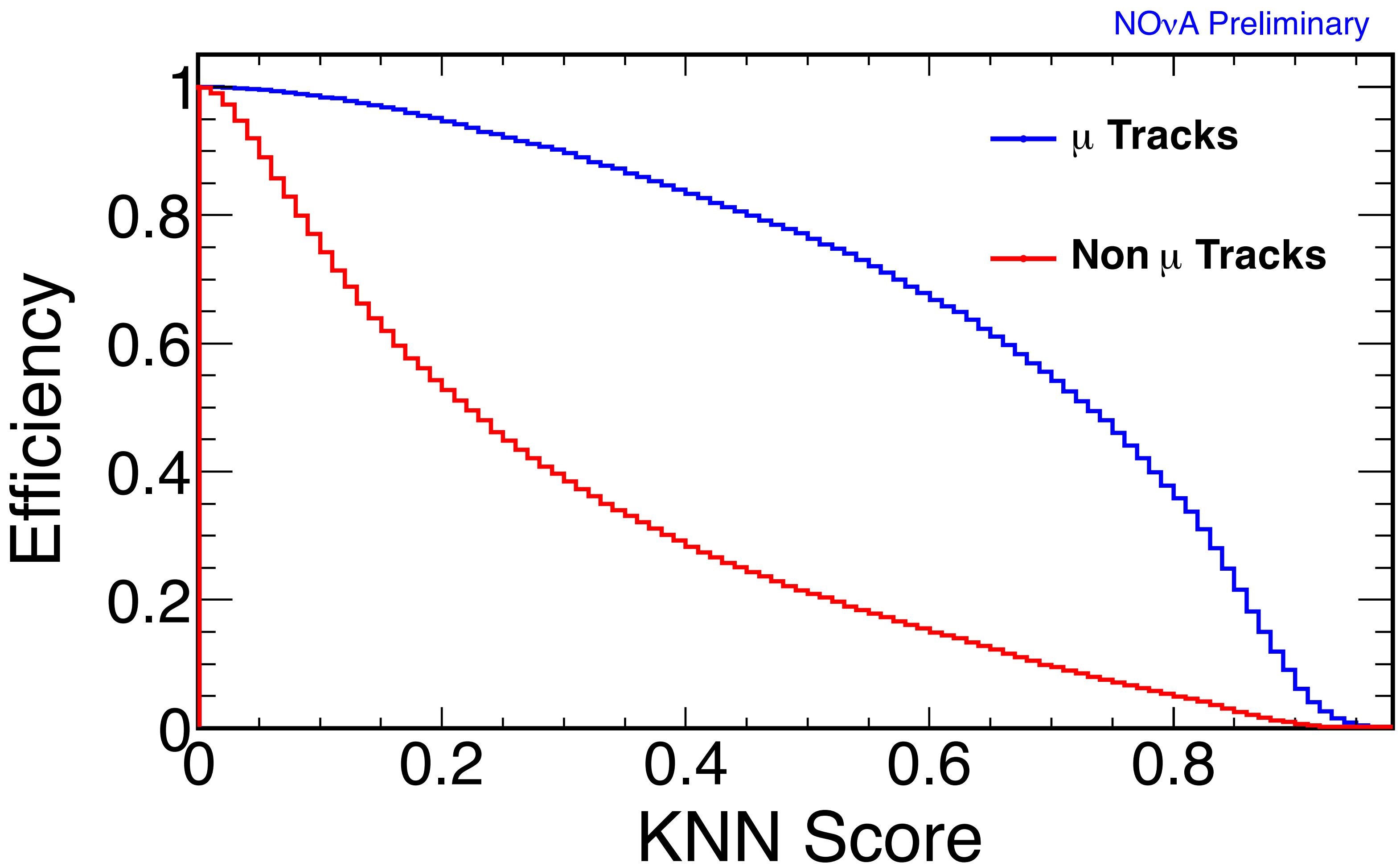






Multivariate analysis developed to identify short muon tracks (< 2m) using reconstructed dE/dx-based measurements.

Measurement of ν_μ CC Inclusive Cross-Section in NDOS

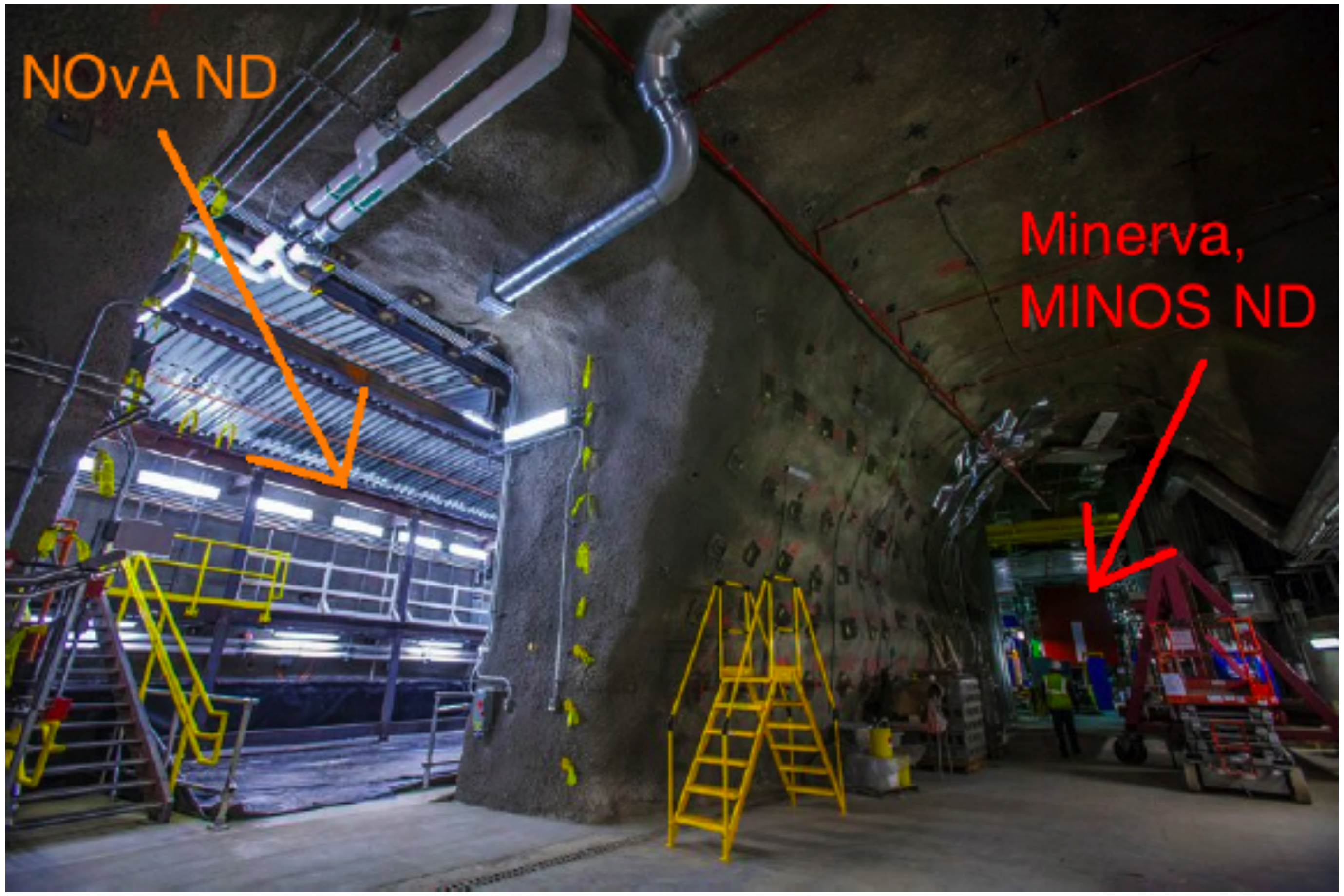


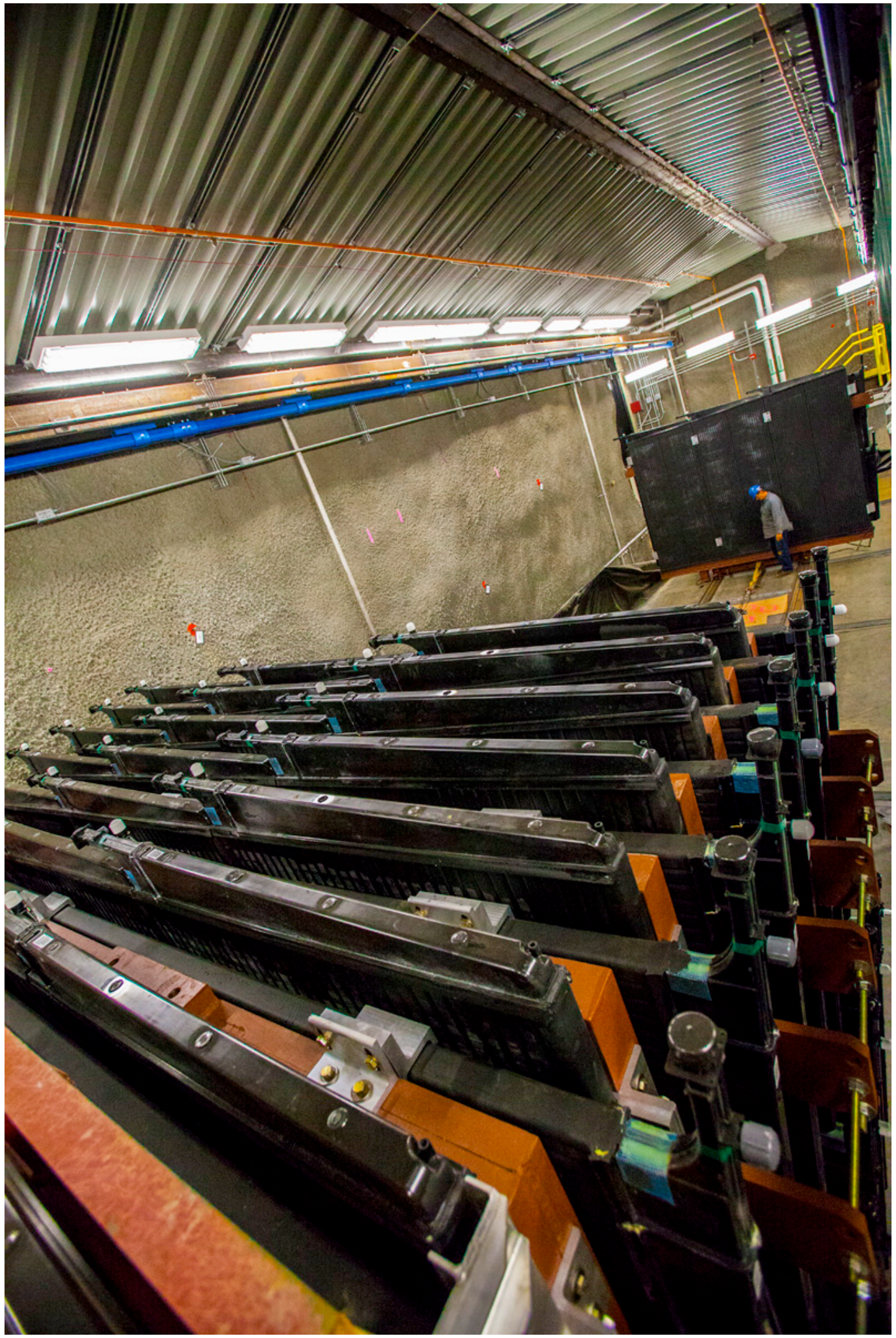
Preliminary results of multivariate analysis to separate short muon tracks from short non-muon tracks.

- Event selection nearly finalized
- Early studies indicate resolution of reconstructed neutrino energy for QE events is ~20%, non-QE events is ~40%.
- Expected statistical uncertainty: < 10%
- If flux uncertainty can be reduced, measurement of cross-section at $E_\nu \sim 2.5$ GeV could be possible at 10-20% level.
- Alternatively could be used to constrain kaon component of off-axis beam.

NOνA Near Detector Construction Progress

- Muon catcher installed Aug. 1, 2013
- First half of Near Detector to be installed by end of this year
- Second half of Near Detector to be installed by summer of 2014





Uses of the NOνA Near Detector

- Measurement of neutrino energy spectrum before oscillation occur
  - Decompose into QE, non-QE, NC
  - Extrapolate to predicted spectrum in Far Detector (see Louise Suter's poster!)
- Physics Analysis Topics:
  - ν_μ and ν_e CC Cross-section measurements
  - Separation of ν_μ and ν_μ-bar QE events (neutron tagging)
    - in-situ measurement of wrong-sign contamination
  - Coherent π^0-like events in non-muon events
    - useful for ν_e appearance measurement
    - important background for LSND/MiniBooNE-like appearance search
  - Magnetic moment of the neutrino

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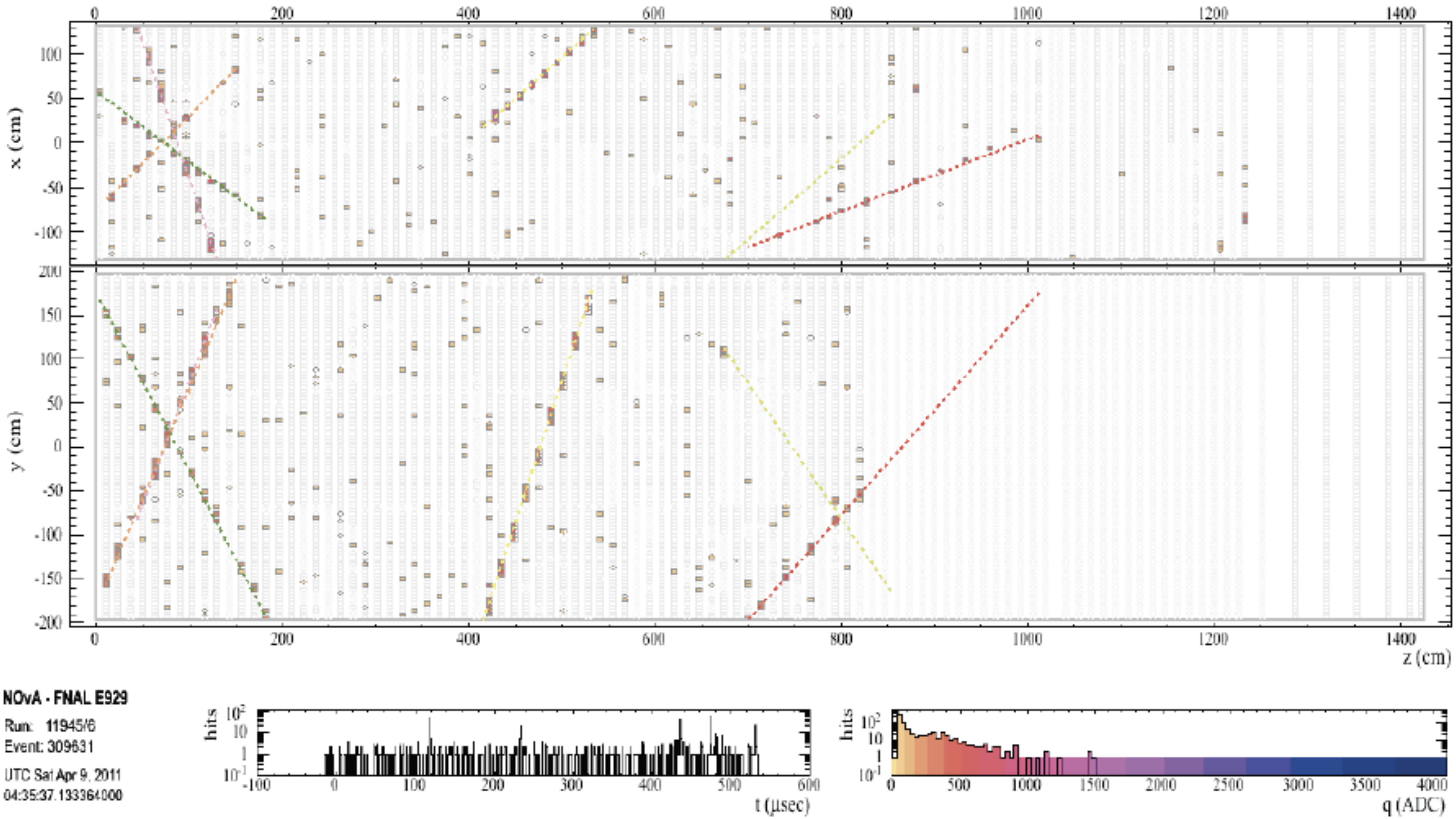
Analyses are at early stages of development

Summary

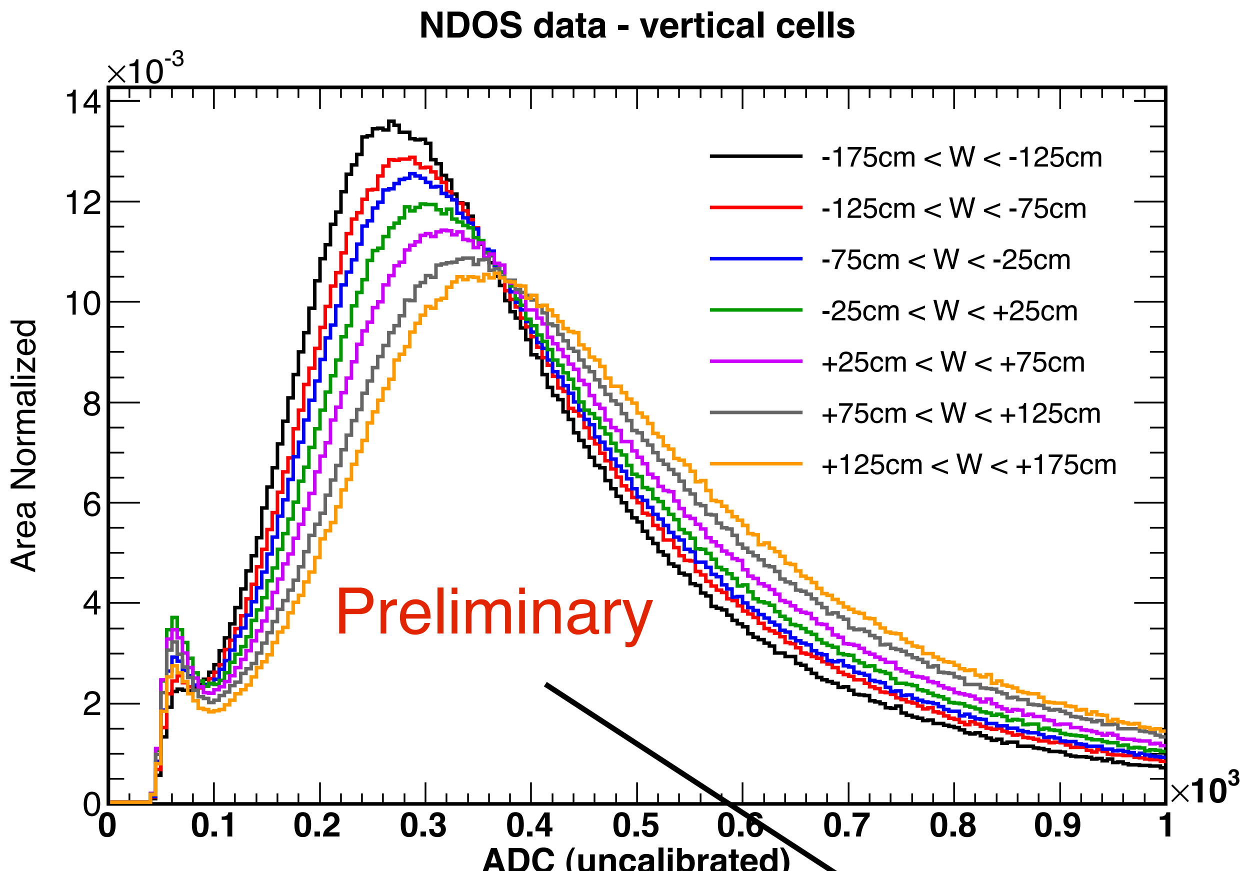
- Off-axis locations of NOvA prototype detector and Near Detector provide unique opportunities for cross-section measurements.
- Partially instrumented surface prototype detector:
  - 106 mrad off-axis from NuMI beam
  - collected ~1.7×10^{20} POT
  - sensitive to kaon production off target
- Near Detector currently under construction
  - 14 mrad off-axis
  - besides being used to predict neutrino spectrum at Far Detector, many other interesting measurements will be pursued
  - narrow band beam at 2 GeV
  - higher flux at 2 GeV than on-axis
  - will be completed by next summer
- Stay tuned!

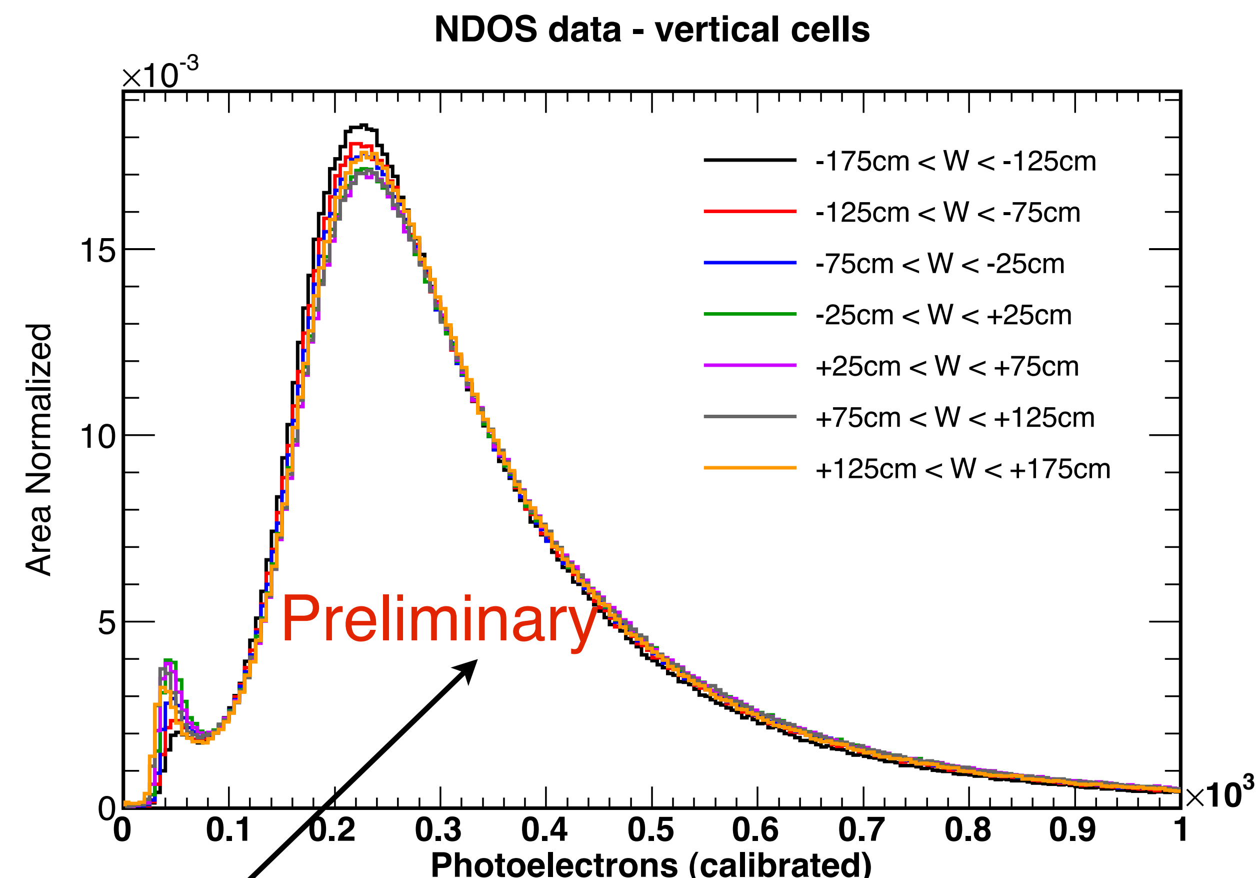
BACKUP

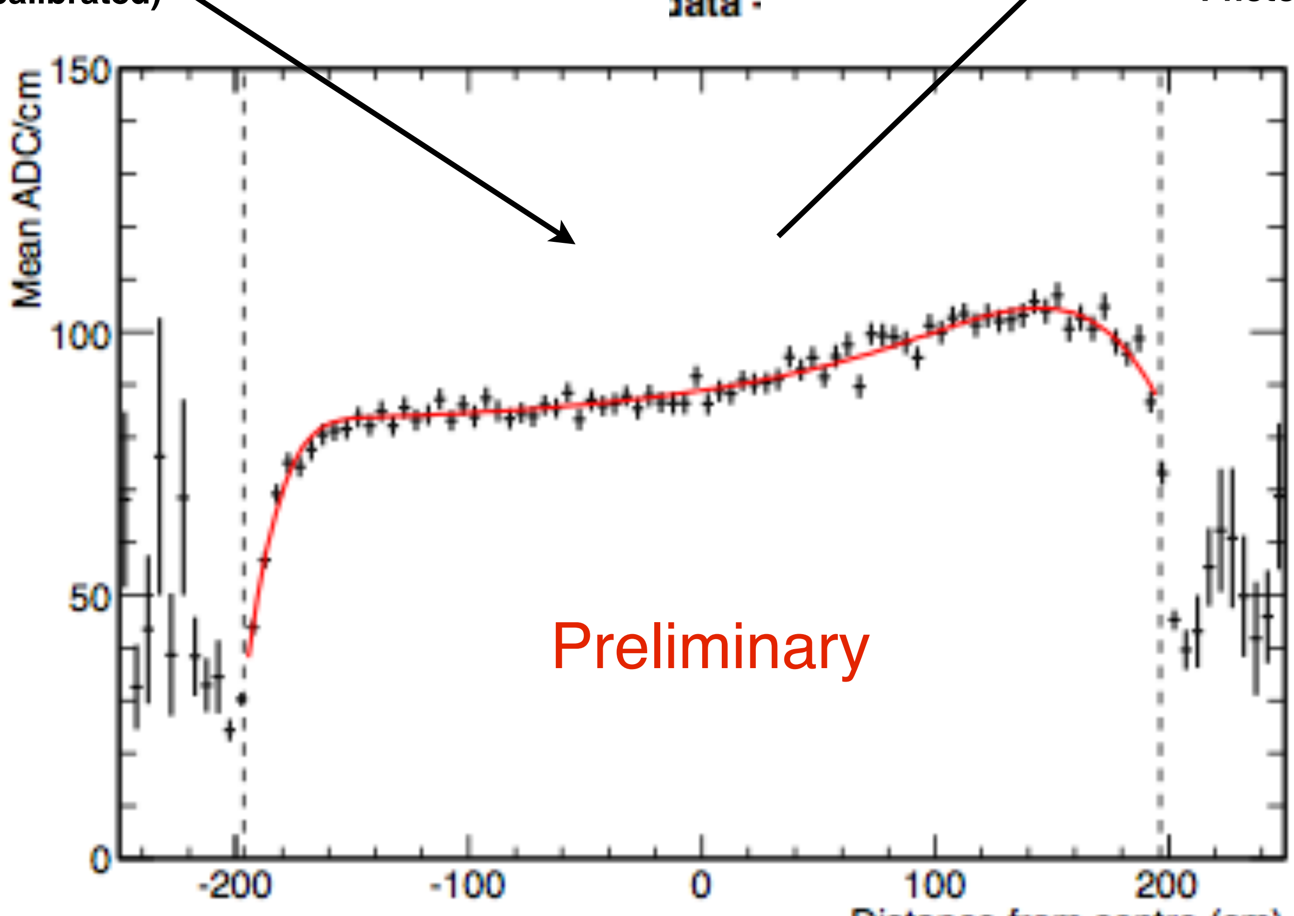
Finding Cosmic Rays in NDOS (not hard!)



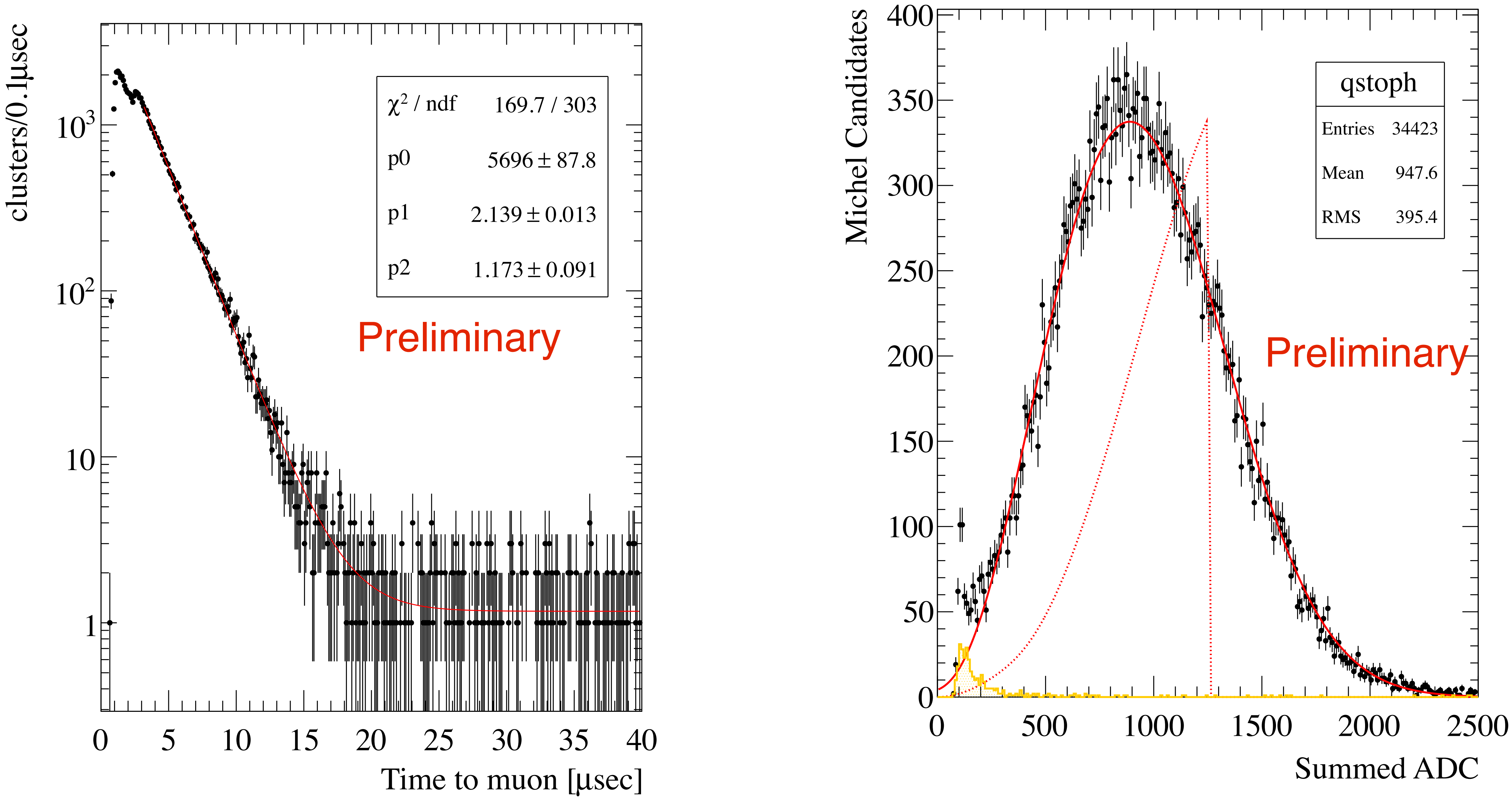
Using Cosmics for Calibration







Michel Electrons



Use Michel electrons for electro-magnetic energy calibration.