Measurements of ν_μ Charged Current Cross Sections Using the NOvA Prototype Detector

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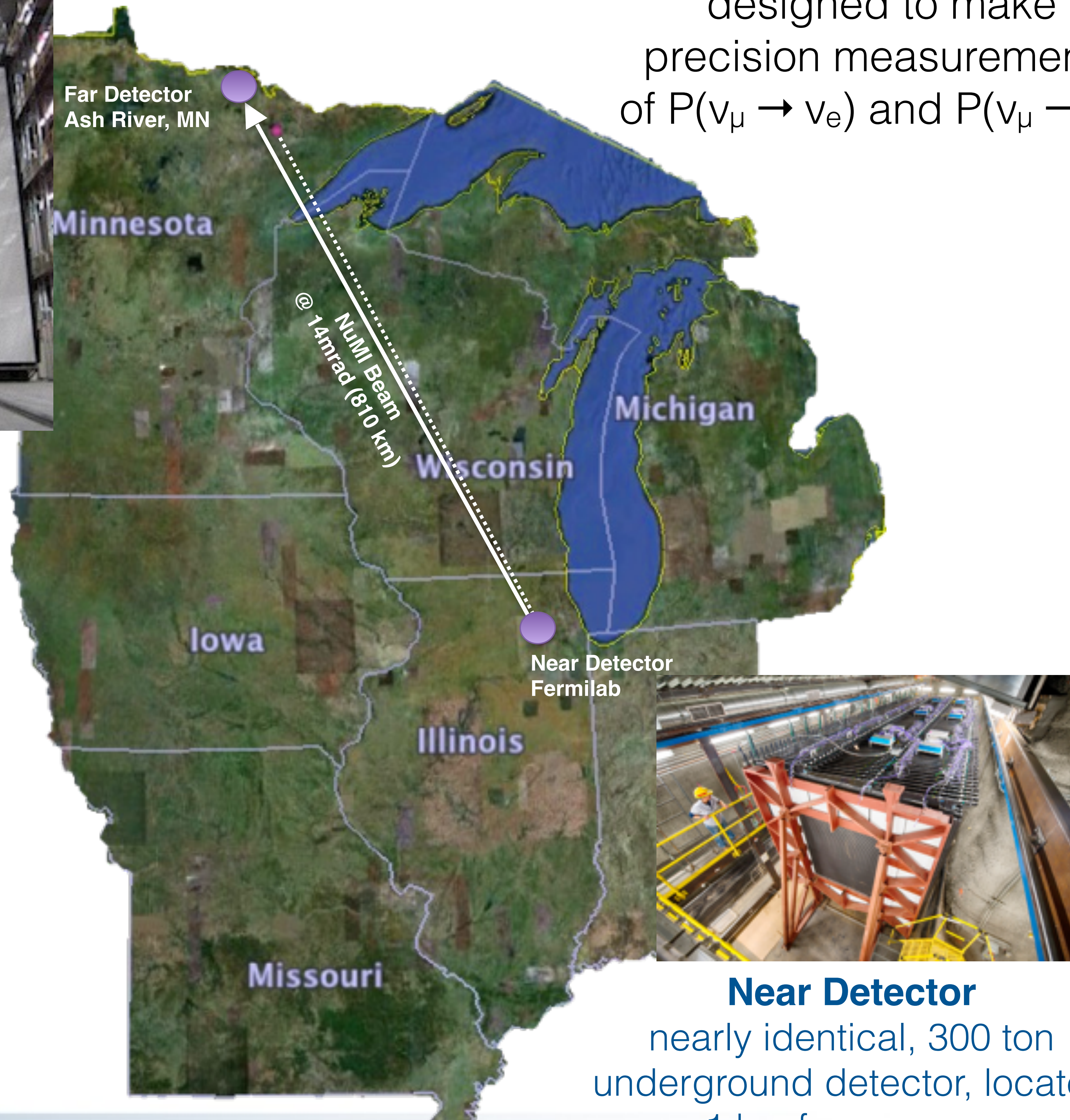
Argonne National Lab

NuFACT 2014
Glasgow, Scotland

The NOvA Experiment

Far Detector
14 kt liquid scintillator tracking calorimeter, located on the surface



designed to make precision measurements of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_\mu)$

NuMI Beam

- upgrade from 360 kW to 700 kW in progress
- 120 GeV protons strike a graphite target to produce pions and kaons
- forward (reverse) horn current mode produces a mostly ν_μ (anti-ν_μ) beam
- off-axis spectrum is sharply peaked around 2 GeV

Near Detector
nearly identical, 300 ton underground detector, located 1 km from source

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14 kt liquid scintillator tracking calorimeter, located on the surface

designed to make precision measurements of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_\mu)$

For more information on the NOvA Experiment, see the talk by Xuebing Bu, (60) "The NOvA Experiment"

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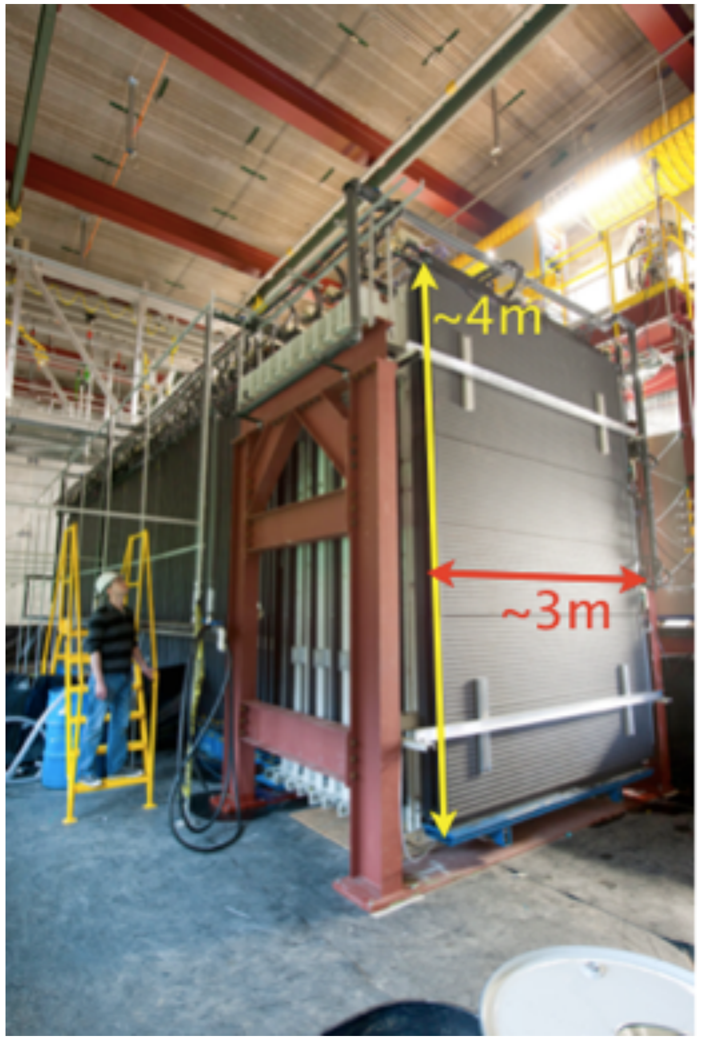
nearly identical, 300 ton underground detector, located 1 km from source

The NOvA Prototype Detector
"Near Detector on the Surface (NDOS)"



Designed to test:

- detector component construction and installation procedures
- all detector systems end-to-end

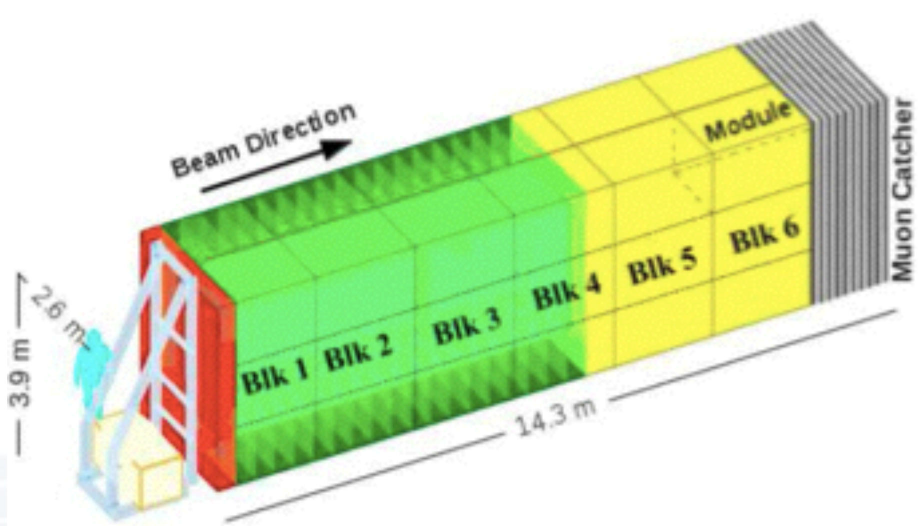
Located 6.1° (110 mrad) off-axis above the NuMI beamline

225 tons, ~3m (w) x ~4m (h) x ~14m (L), 199 planes of LS-filled PVC modules

Muon catcher at end of detector used to measure energy of muons

Installation was completed May 9, 2011.

Commissioning and data collection has been on-going since November 2010.



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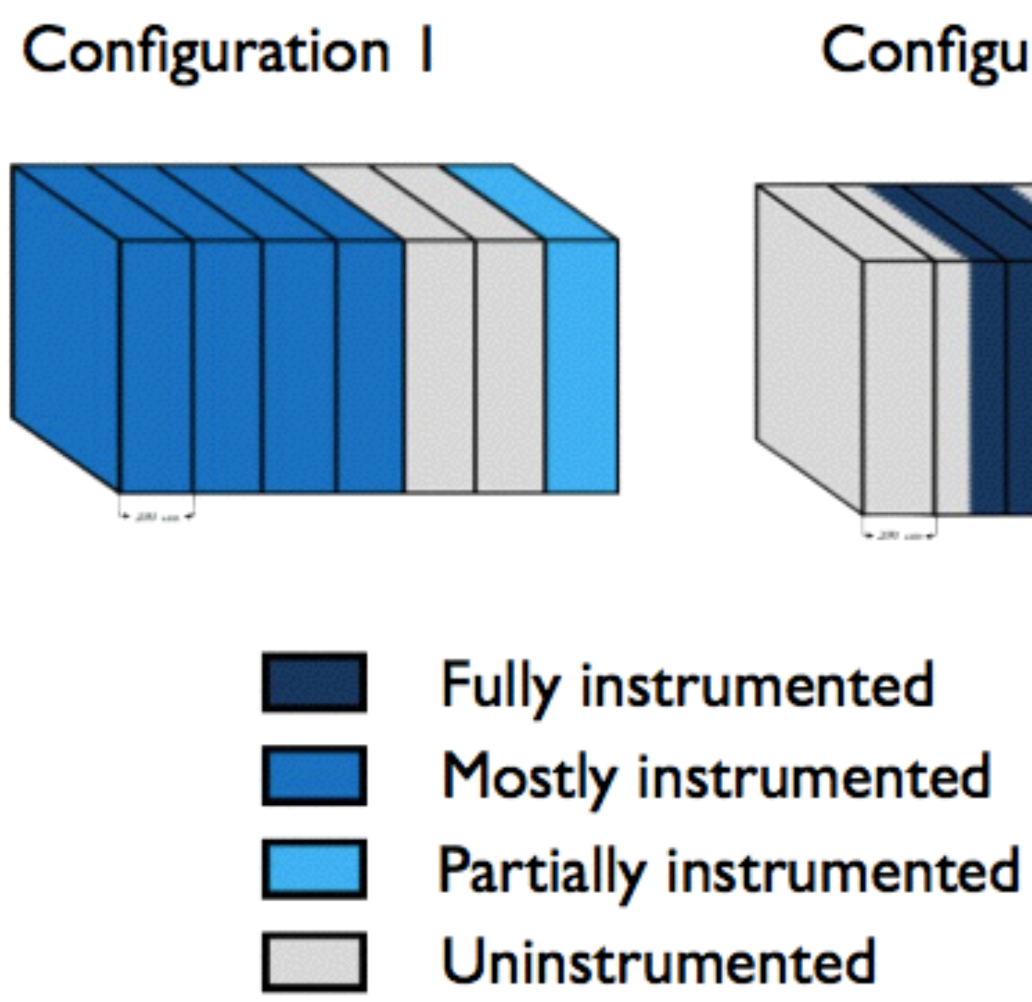

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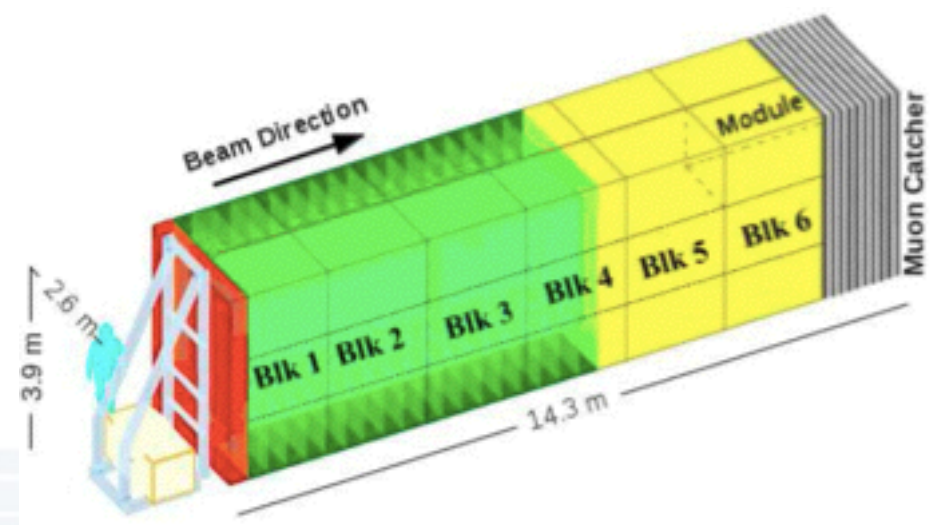
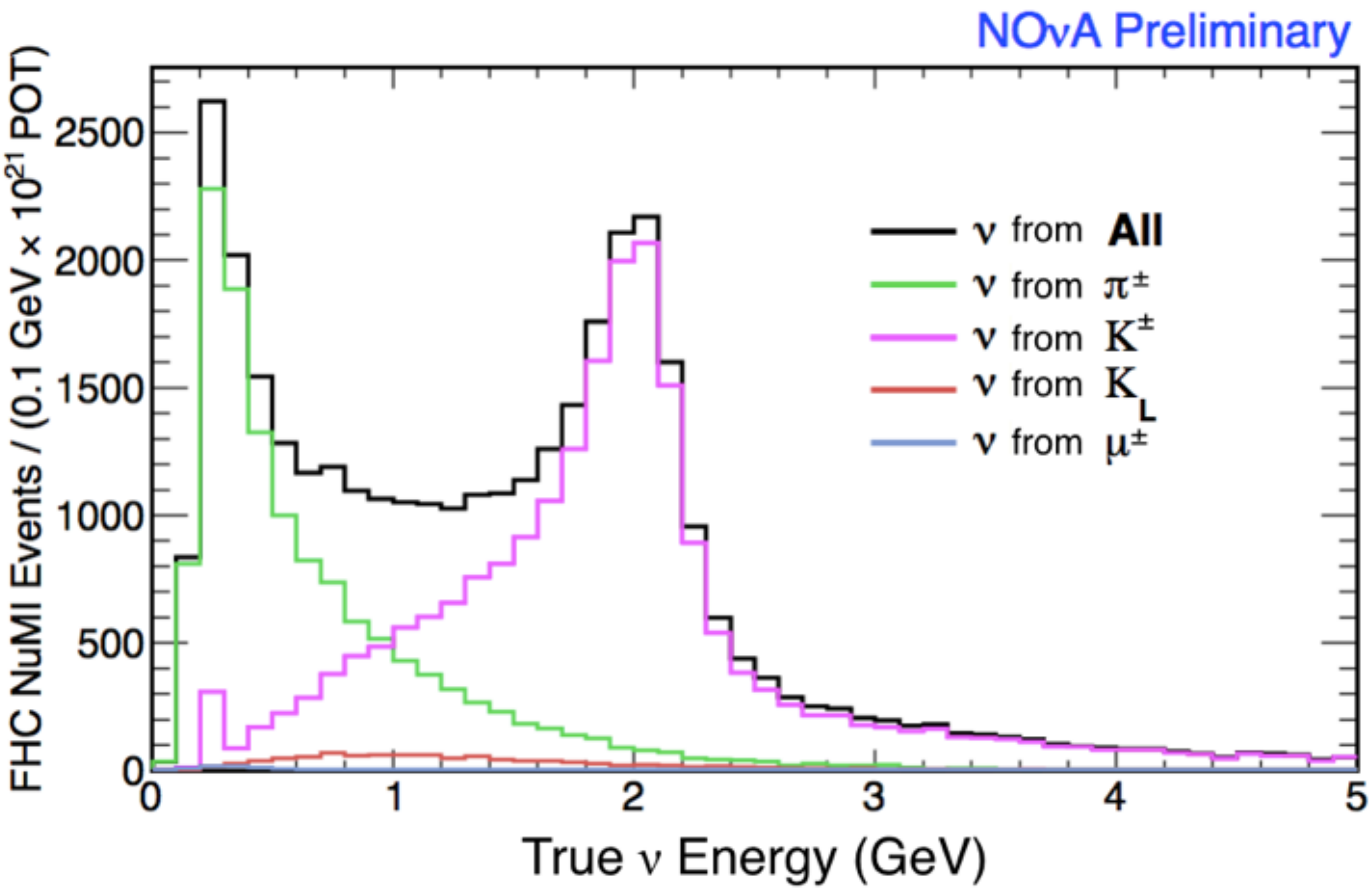
Muon catcher at end of detector used to measure energy of muons

Config 1 (Apr `11-May `11): 9.6×10^{18} POT

Config 2 (Oct `11-Apr `11): 1.7×10^{20} POT

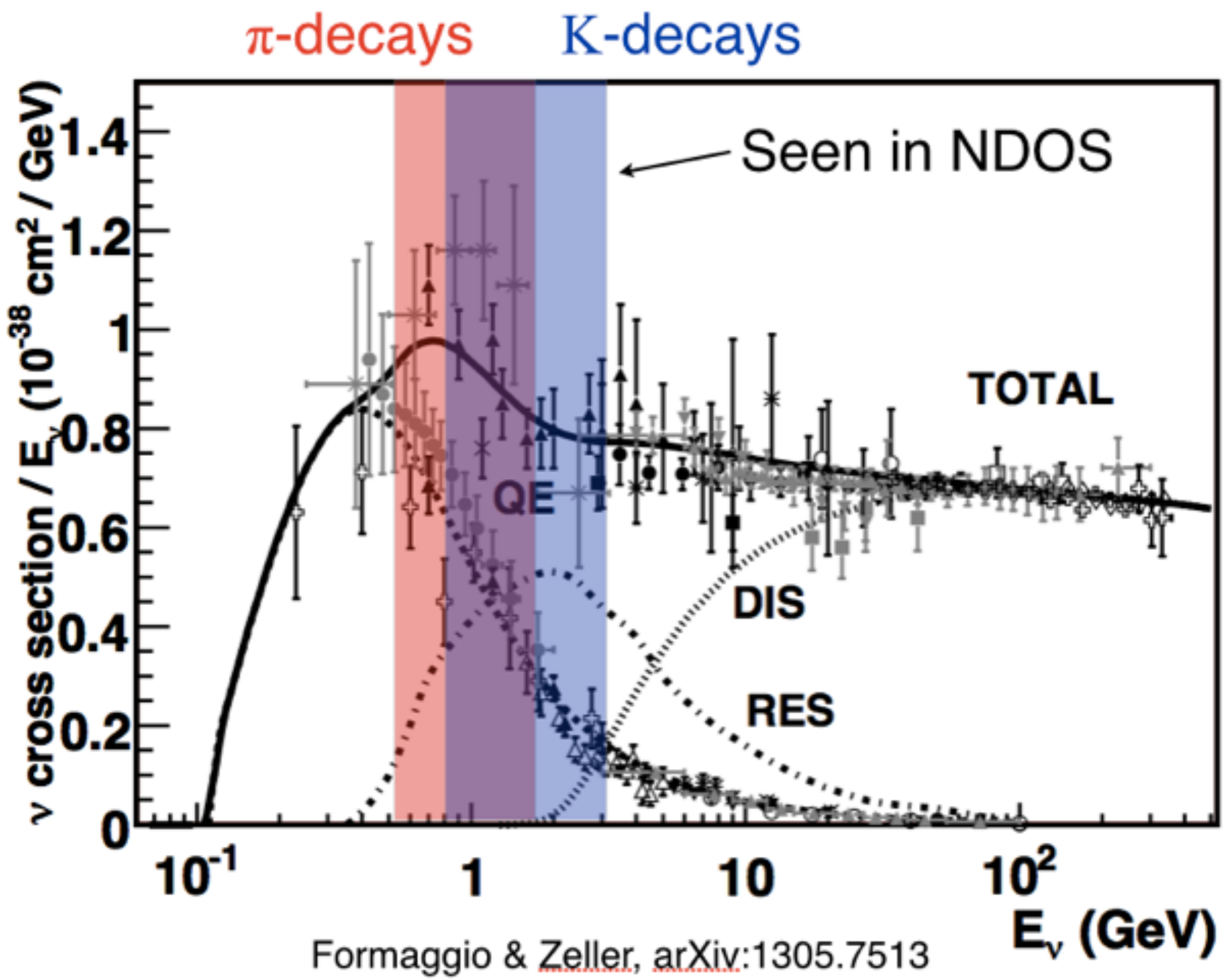


NDOS NuMI Beam Spectrum



ν energy spectrum observed with NDOS has two peaks, the pion peak around 0.3 GeV and the kaon peak around 2 GeV.

NDOS Cross Section Measurements



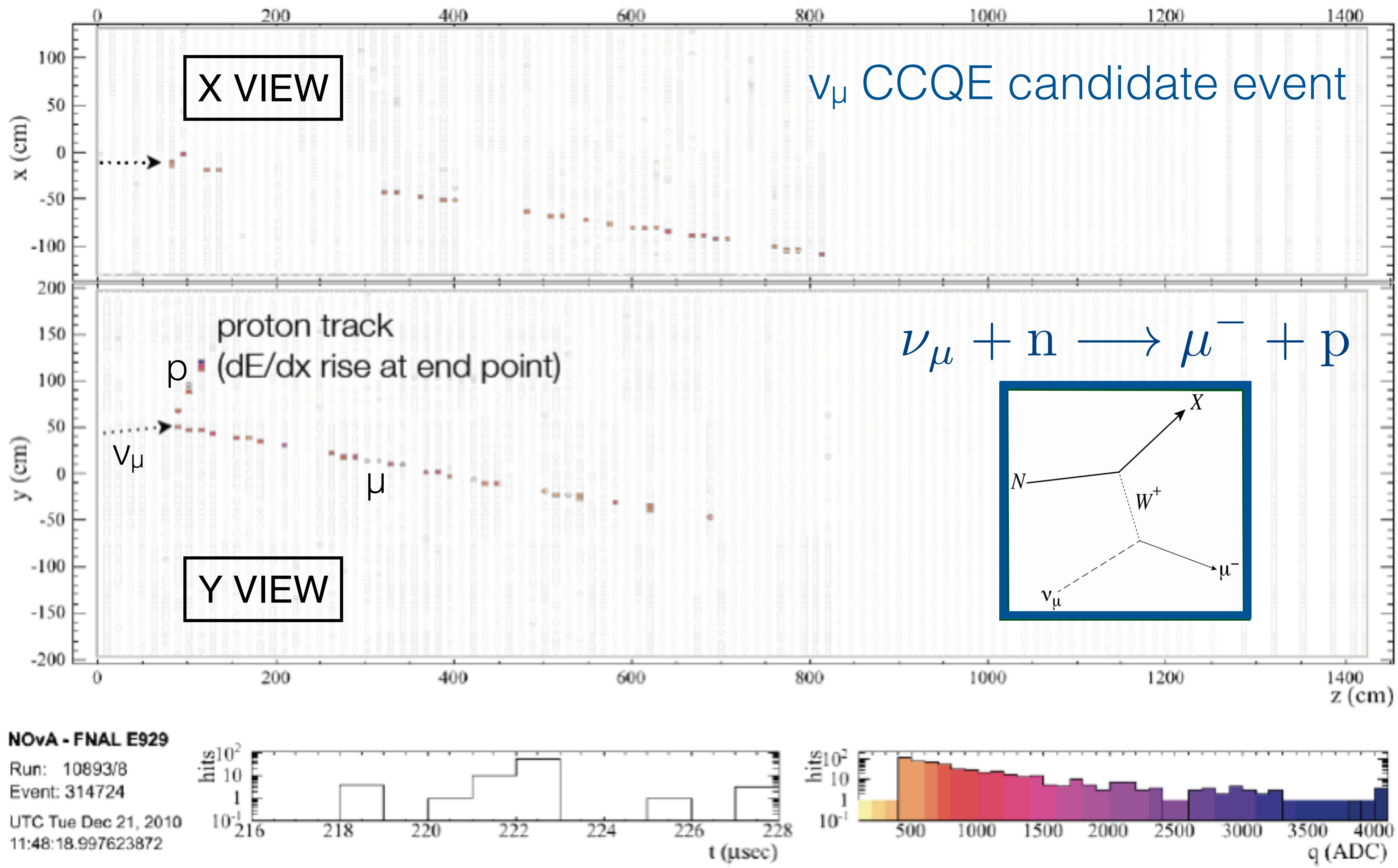
NDOS is sensitive to energies where quasi-elastic (QE) and resonance (RES) interactions dominate. At the lower energies, the neutrinos come mostly from pion decays, while at the higher energies, the neutrinos come mostly from kaon decays.

Measurement of the ν_μ Charged Current Quasi-elastic (CCQE) Cross Section

Minerba Betancourt, Ph.D. Thesis
University of Minnesota, June 2013

http://nova-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=9359

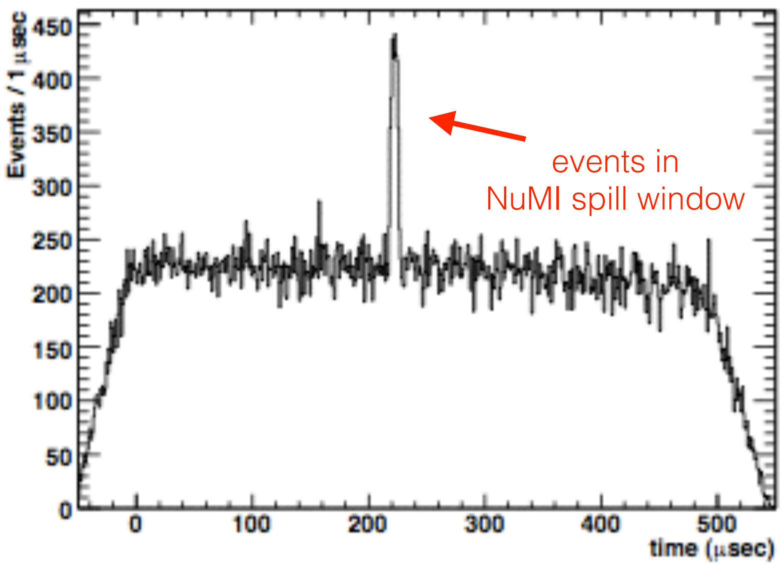
ν_μ CCQE Event Selection



ν_μ CCQE Event Selection

Pre-selection criteria reduce background from cosmic rays and neutral current events

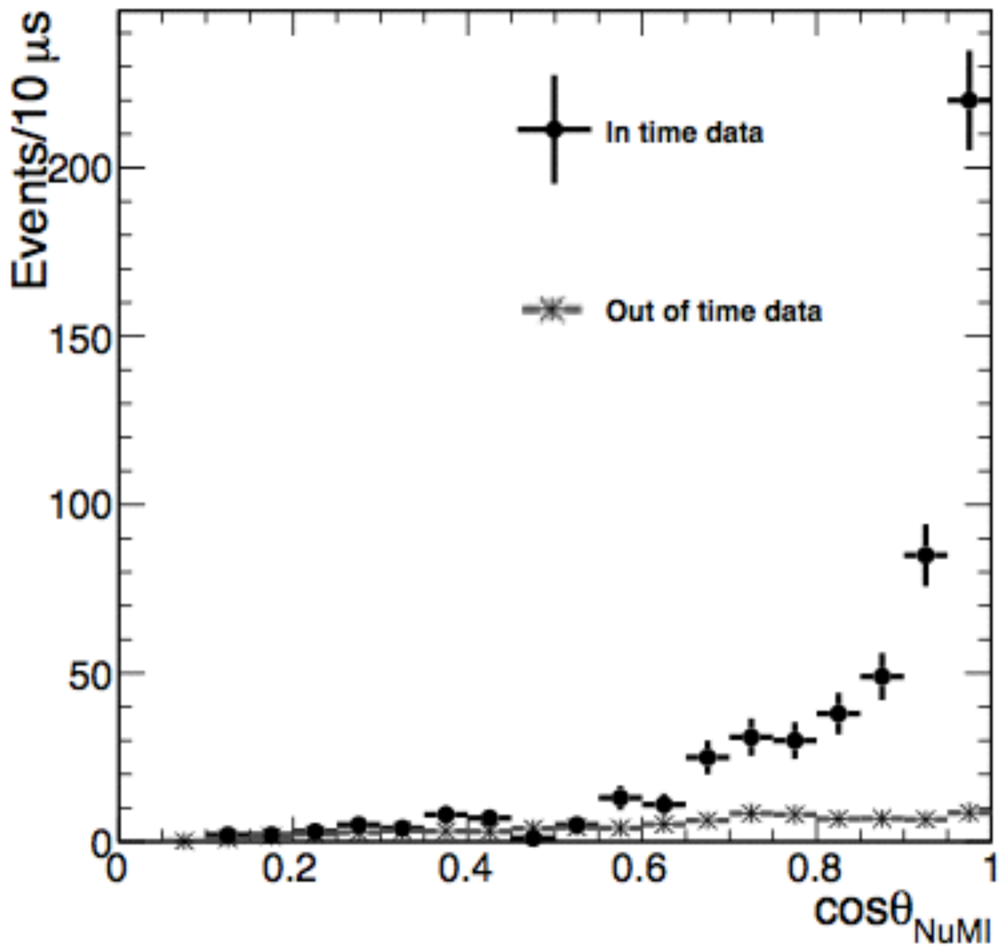
- timing within NuMI beam spill window
- fiducial cuts on vertex position
- **one** reconstructed, 3D, contained track with length greater than 60 cm (only ~4% of ν_μ CCQE events have a reconstructed proton track)
- vertical slope of track < 45^o
- containment fiducial cuts

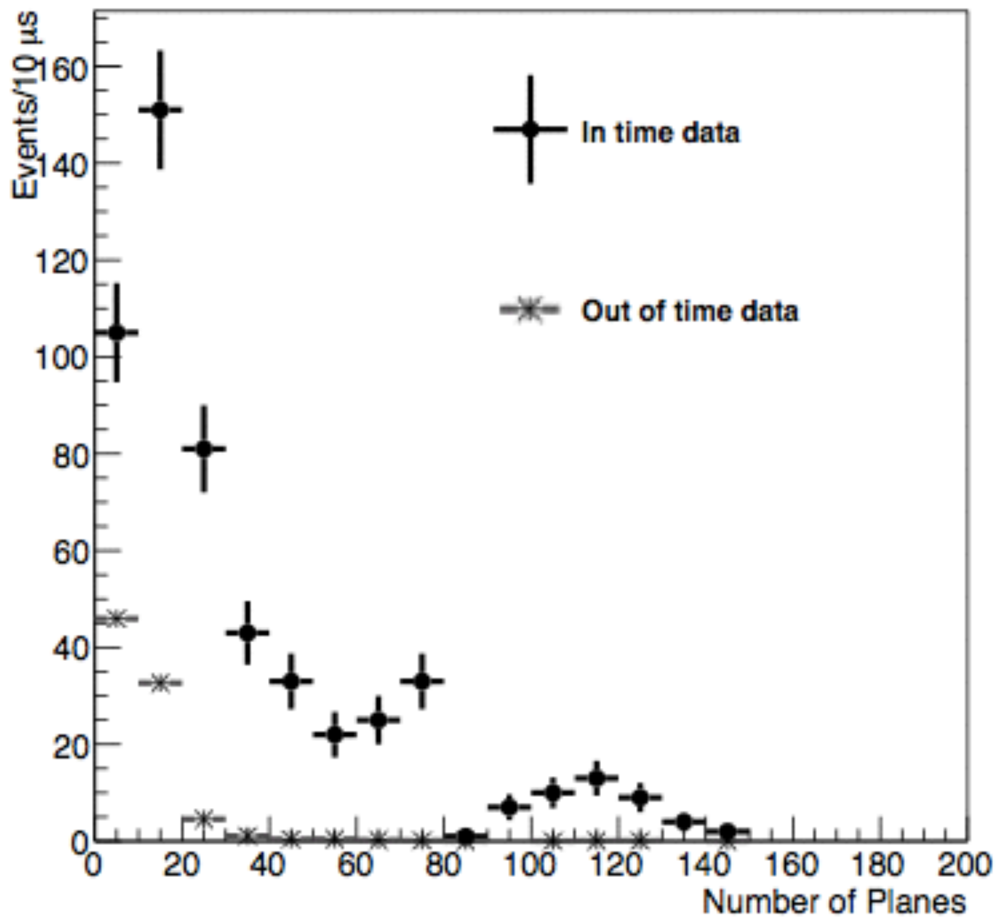


k-Nearest Neighbor (kNN) algorithm selects CCQE events based on 3 parameters

- number of planes that the track crosses (charged pions from NC events travel through fewer planes than muons)
- ratio of mean energy per plane to track length in plane (CC events deposit less energy per plane than NC)
- deposited energy within a 50 cm radius of the vertex, includes muon track hits (CCQE events deposit less E around vertex than other types of interactions)

ν_μ CCQE In-time vs. Out-of-time Data after Pre-selection



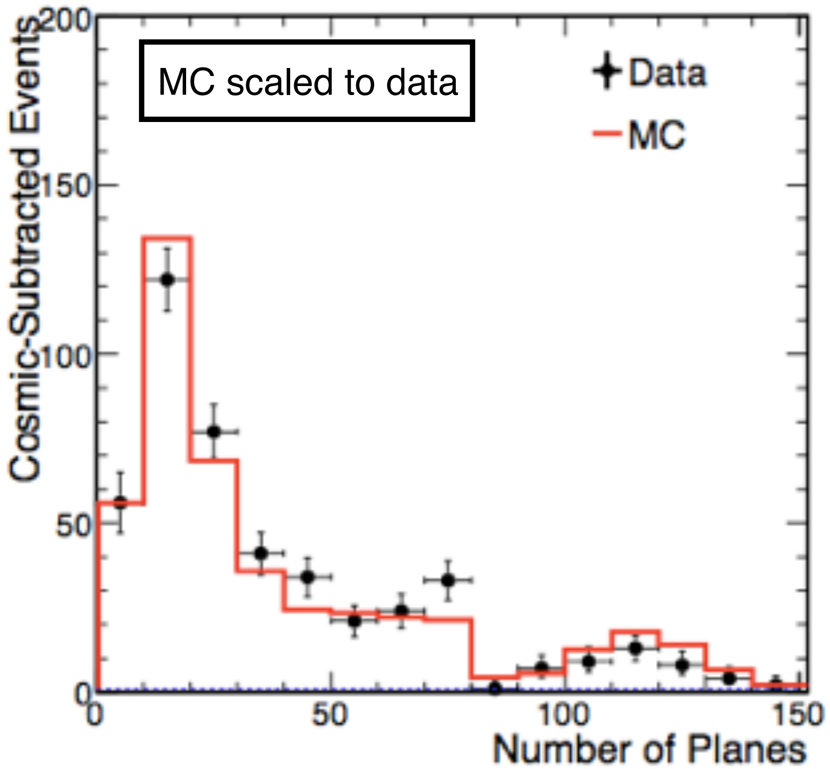


LEVEL OF RESIDUAL COSMIC RAY BACKGROUND IN DATA AFTER PRE-SELECTION

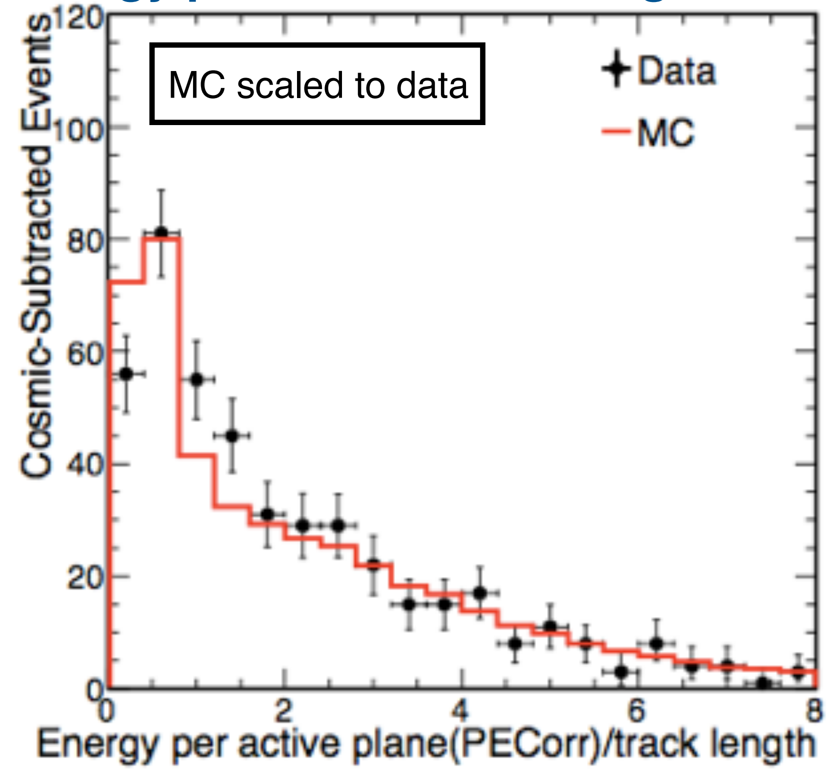
- in-time data include neutrino interactions as well as CR backgrounds
- out-of-time data sample contains ~49x more data than in-time sample (statistical uncertainties small compared to that of in-time data)
- exposure-weighted out-of-time distributions are subtracted from in-time data after CCQE event selection with the kNN classifier

ν_μ CCQE - kNN Algorithm

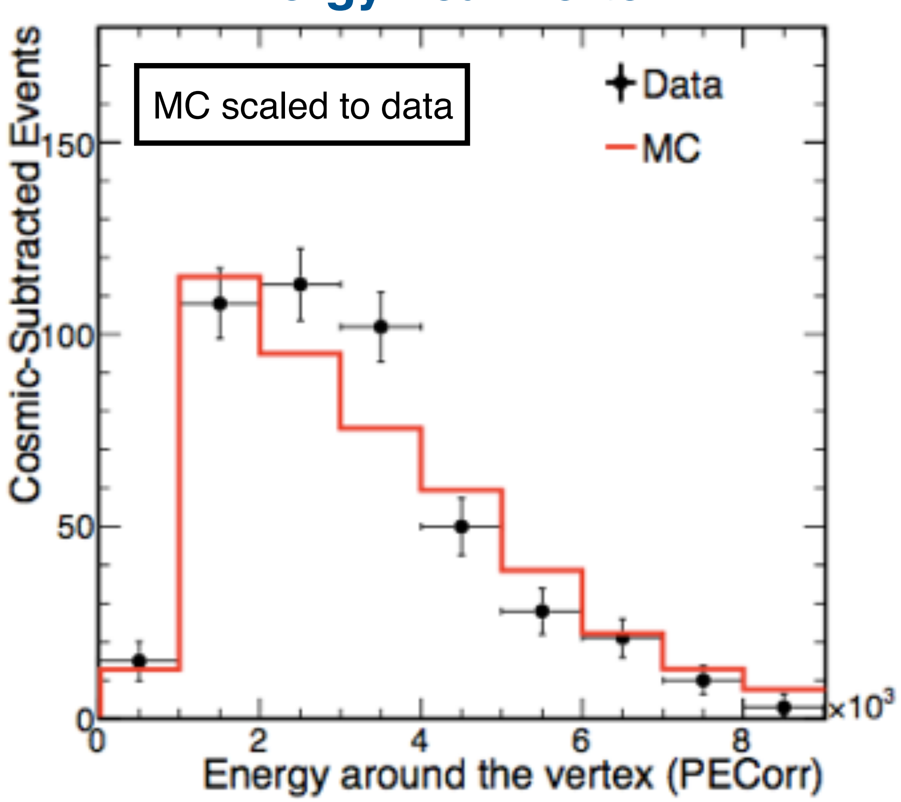
Number of Planes



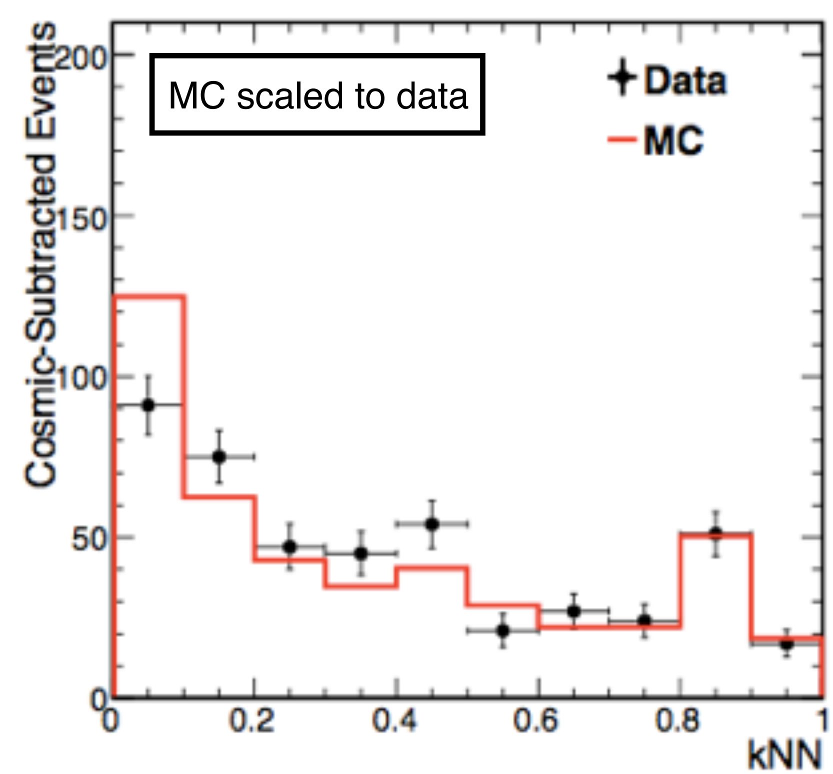
Energy per Plane/Track Length in Plane



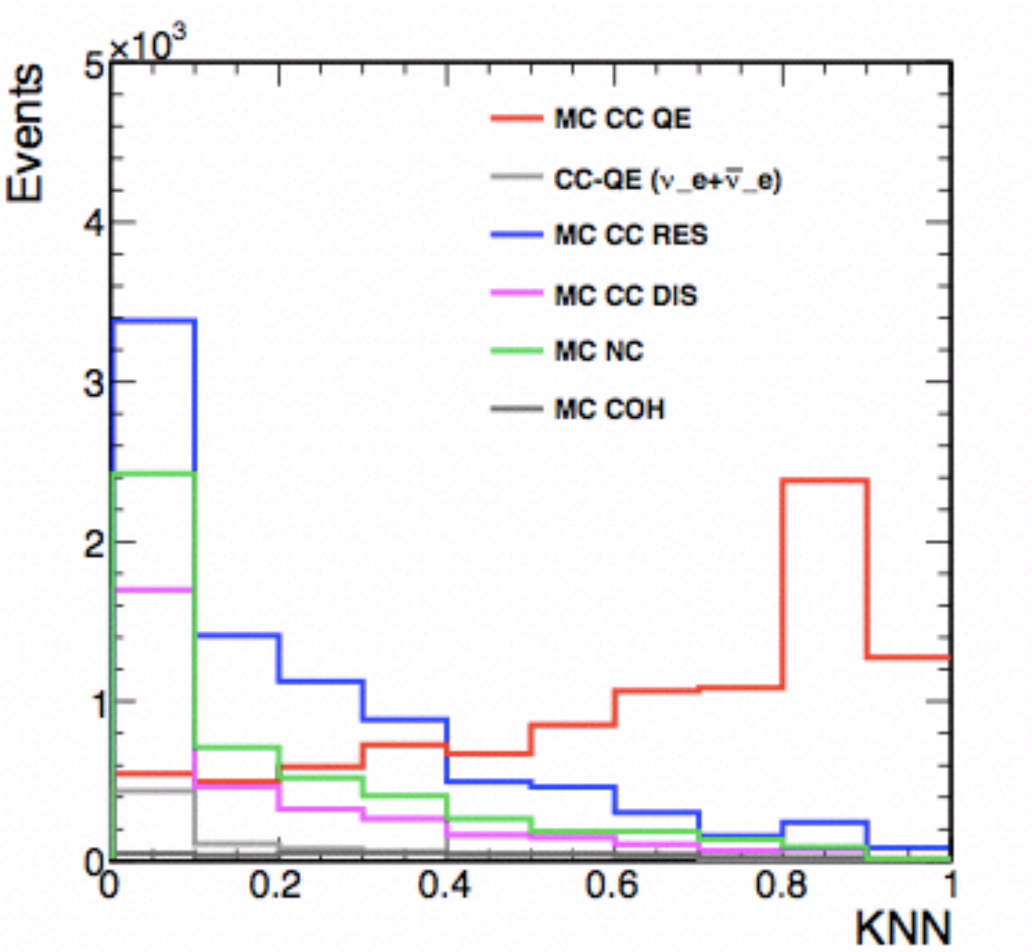
Energy near Vertex

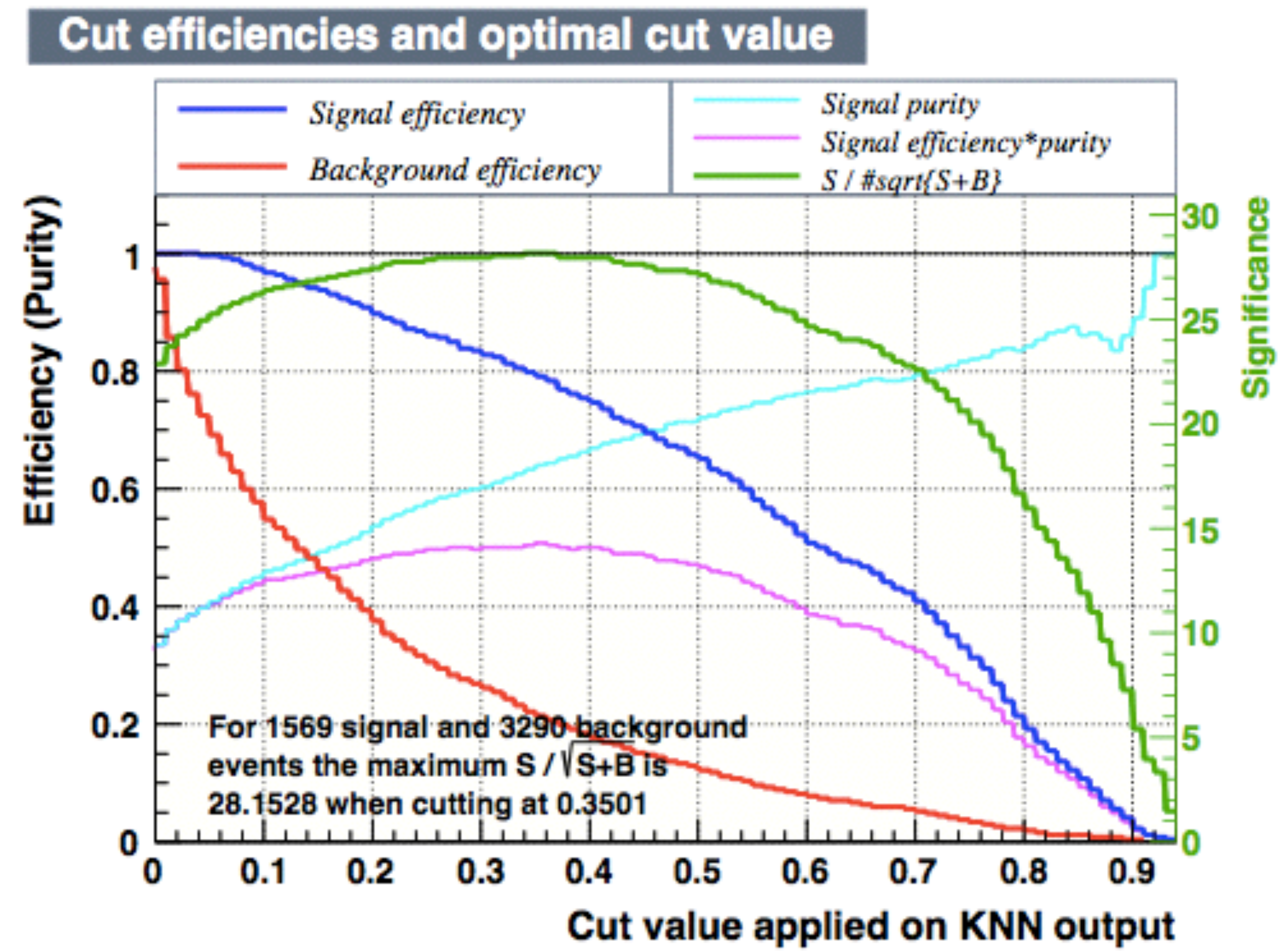


kNN

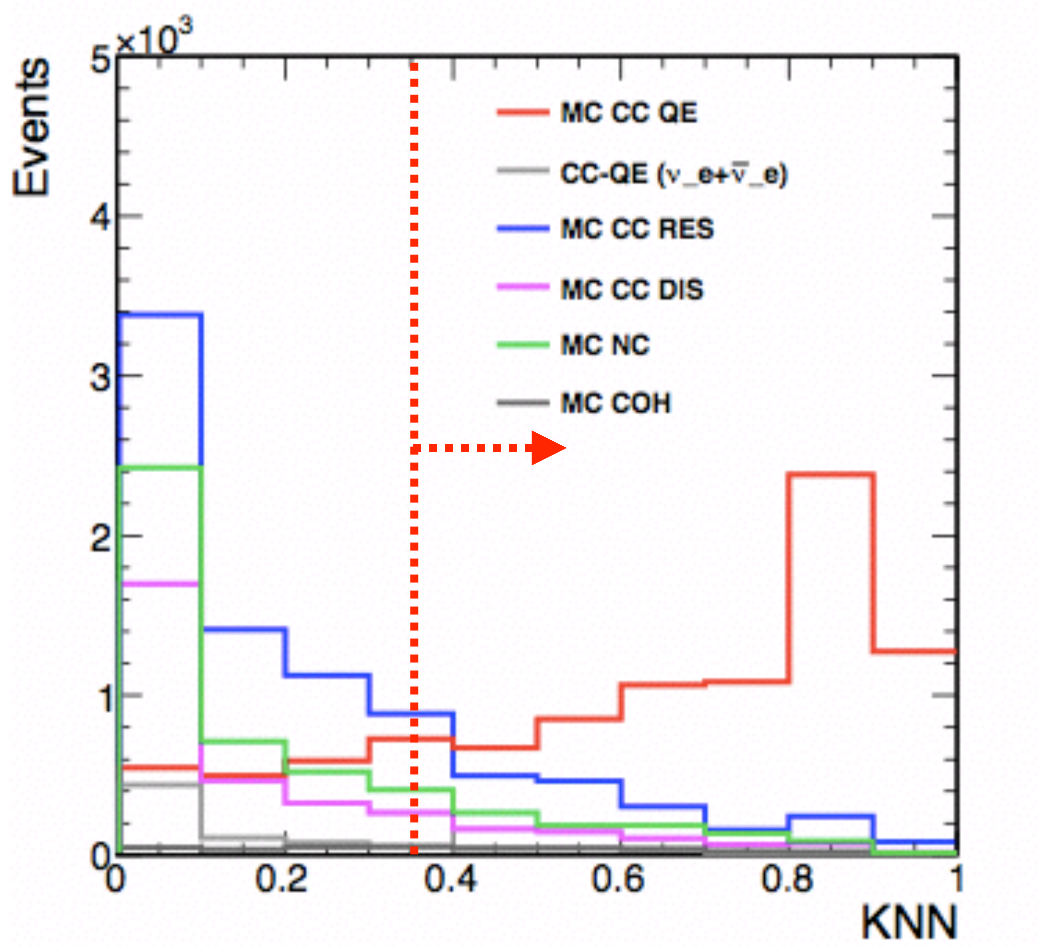


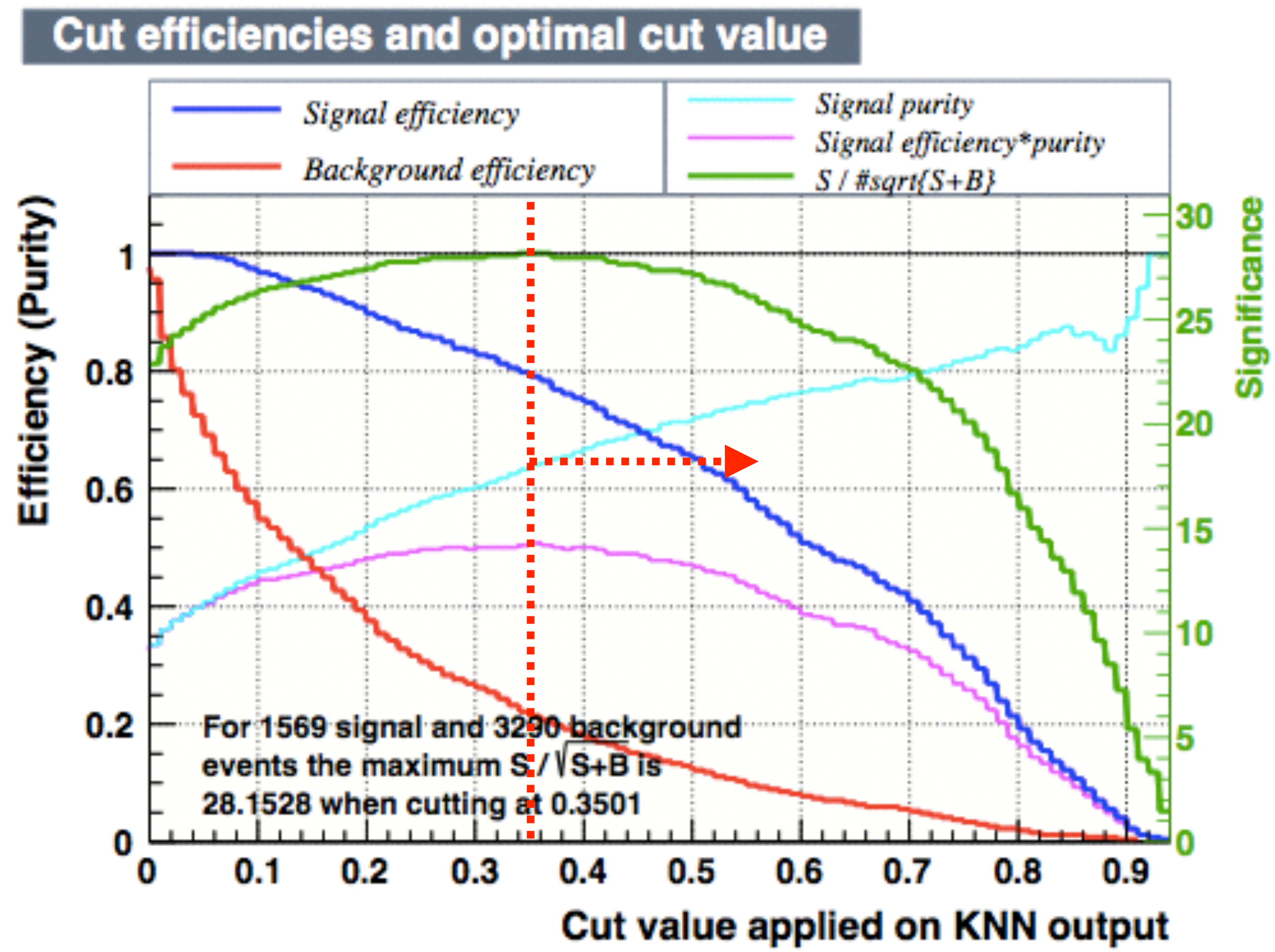
ν_μ CCQE - kNN Algorithm





ν_μ CCQE - kNN Algorithm





kNN selector > 0.35

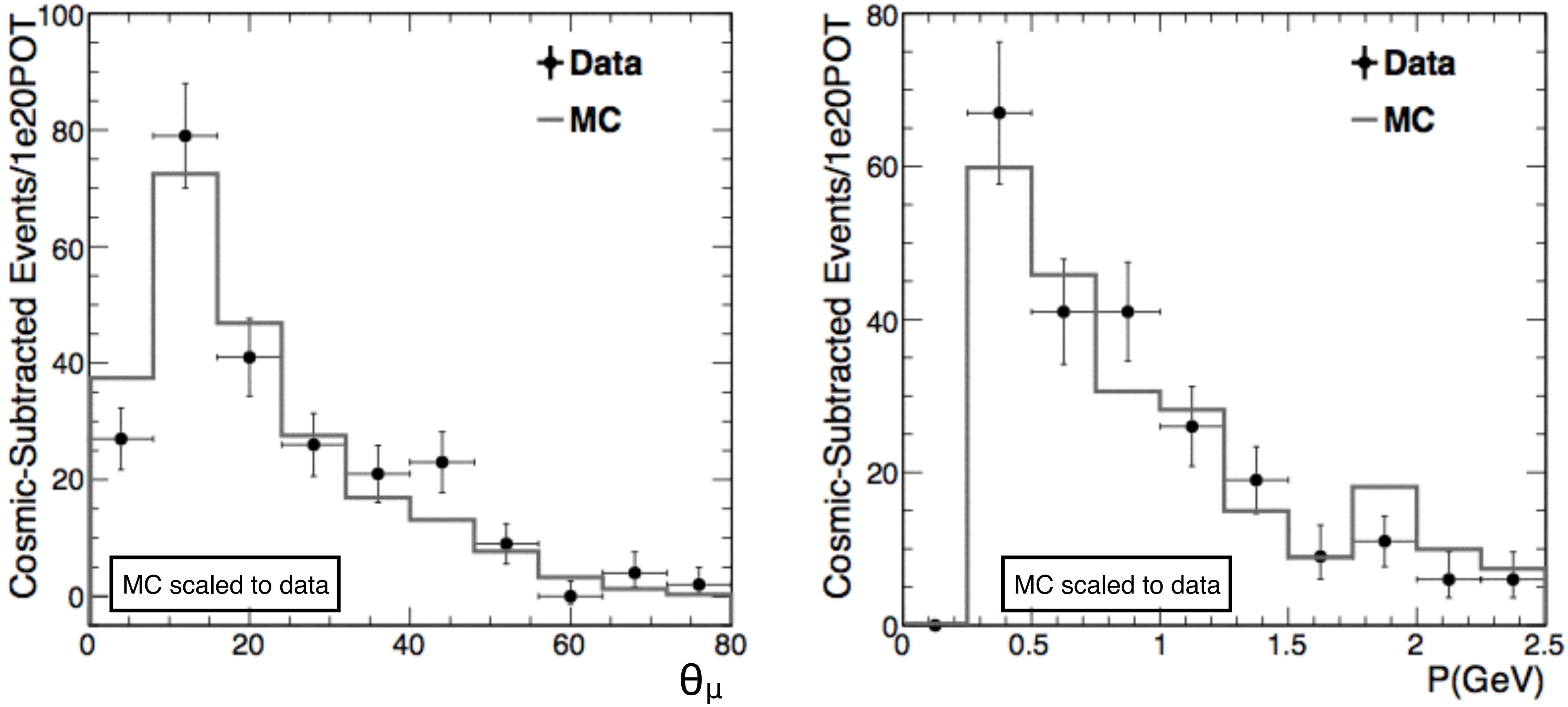
$$\mathrm{FOM} = S/\sqrt{S+B} = 28$$

efficiency = 85%

purity = 65%

Config 1: 55 candidate events, 11 predicted cosmic-ray events
Config 2: 230 candidate events, 20 predicted cosmic-ray events

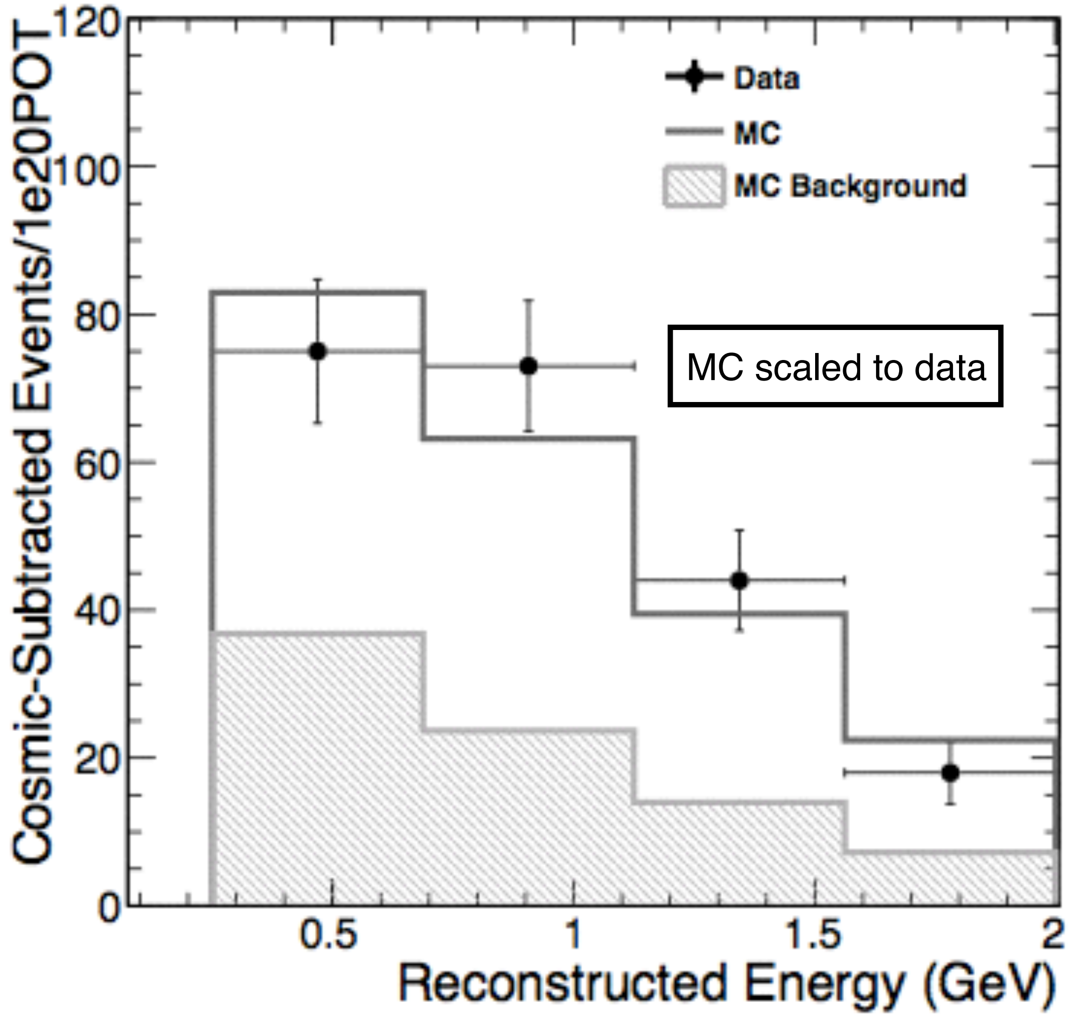
ν_μ CCQE - Reconstruction of Neutrino Energy and Four Momentum Transfer

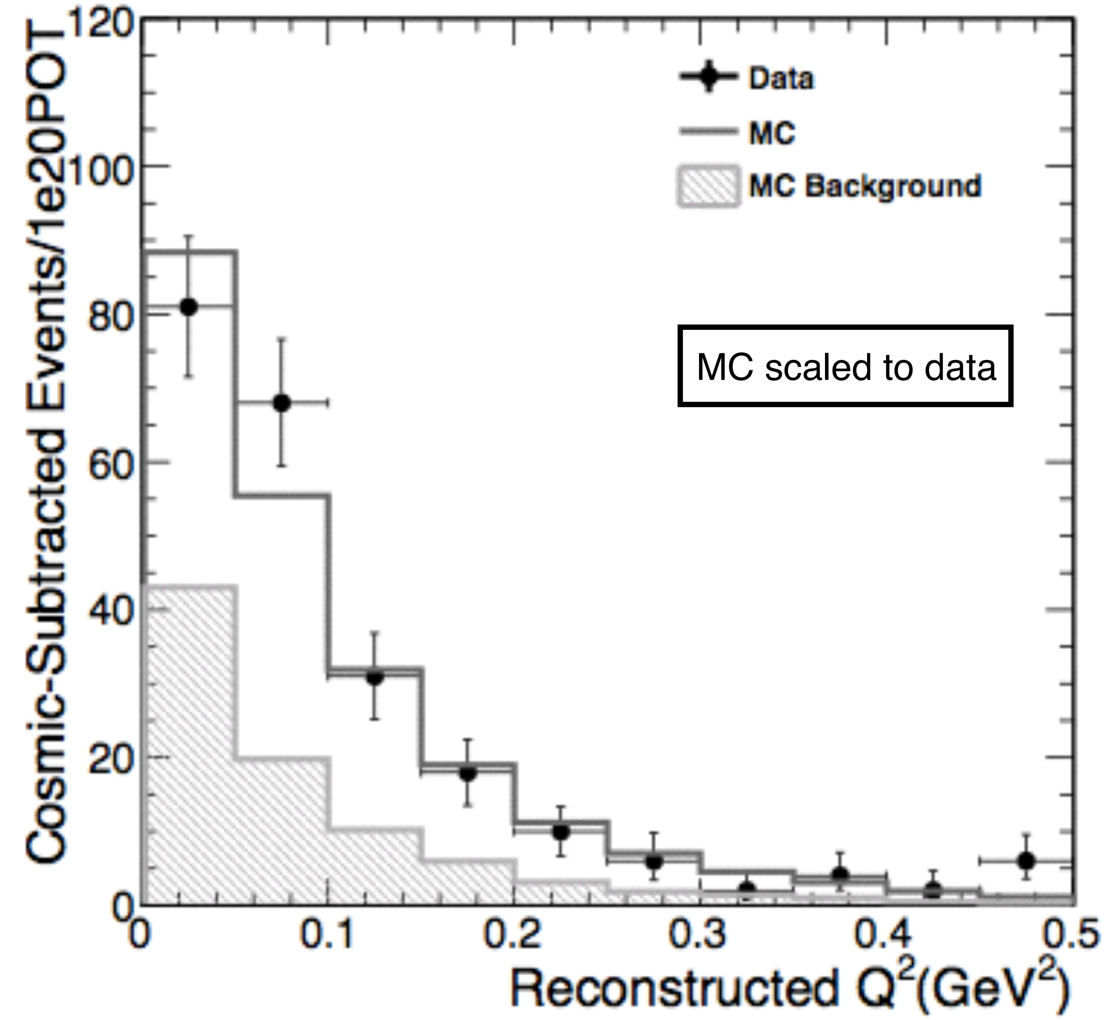


Neutrino Energy: $$E_\nu = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2[(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}$$ $$E_\mu = T_\mu + m_\mu$$

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

ν_μ CCQE - Reconstruction of Neutrino Energy and Four Momentum Transfer





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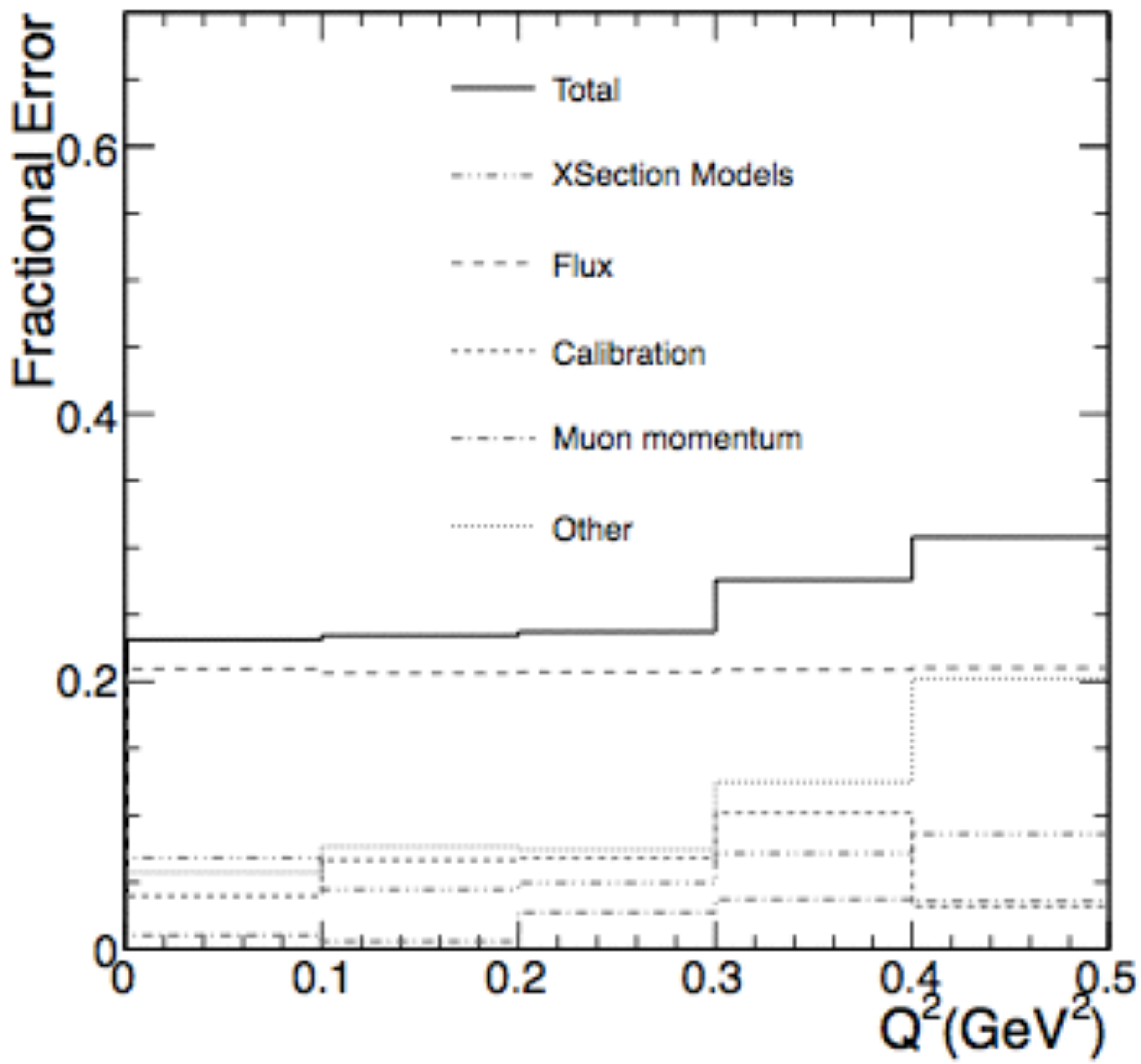
Four Momentum Transfer: $$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu)$$

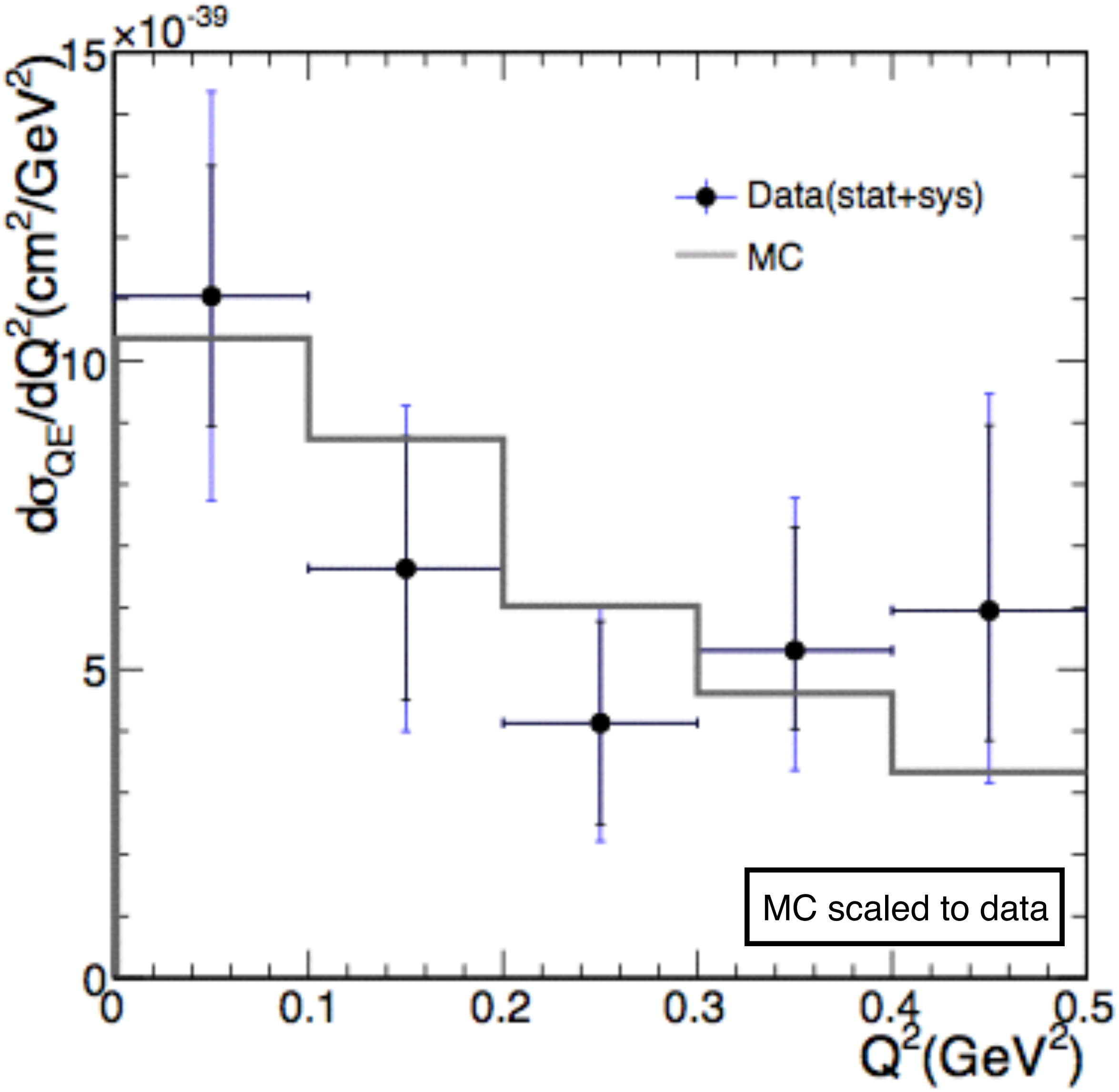
ν_μ CCQE - Systematic Uncertainties

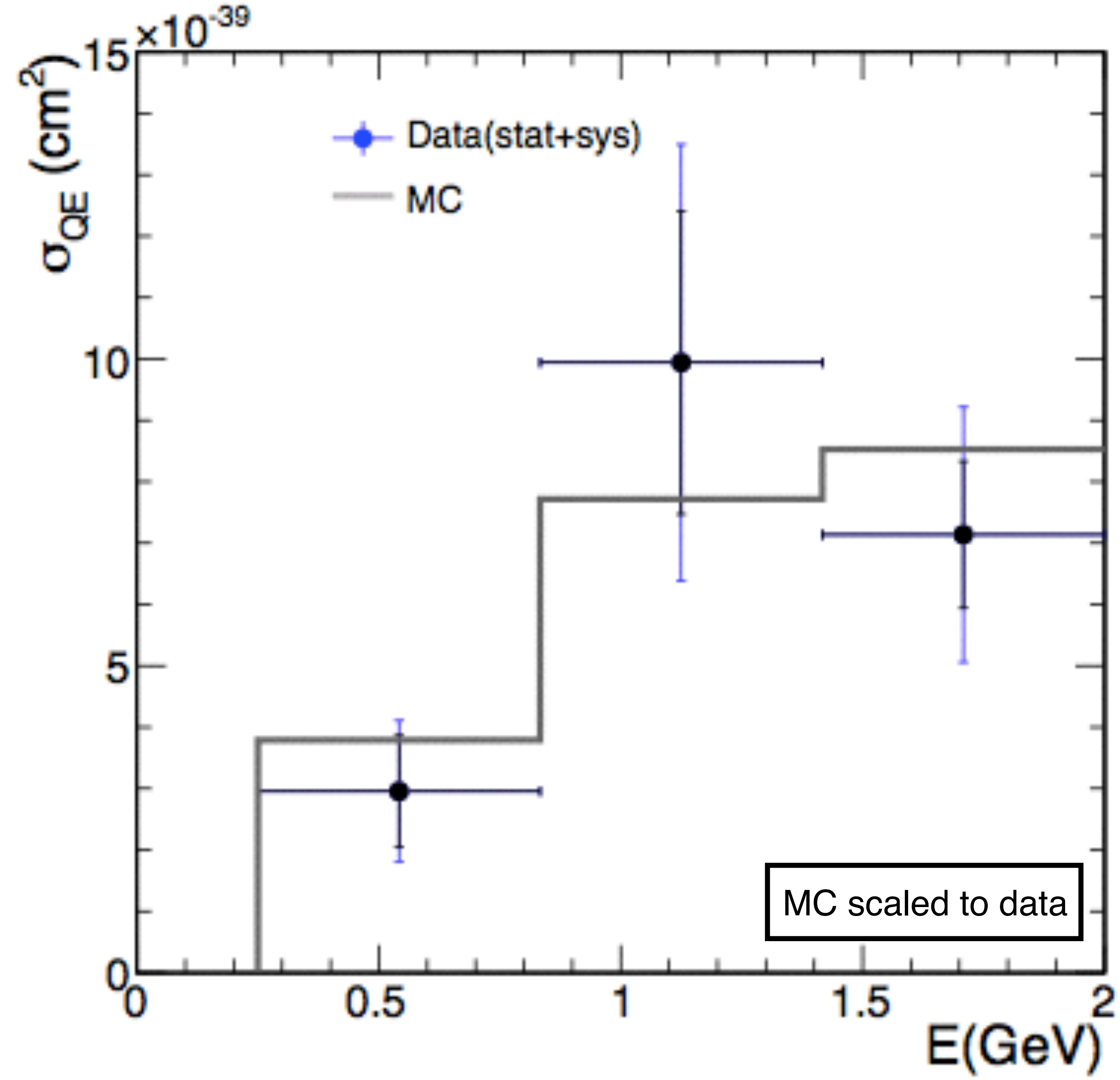


Systematics are dominated at all Q^2 by uncertainty in NuMI beam flux (mostly from hadron production off the NuMI target).

There is an almost equal contribution coming from detector alignment and performance at high Q^2.

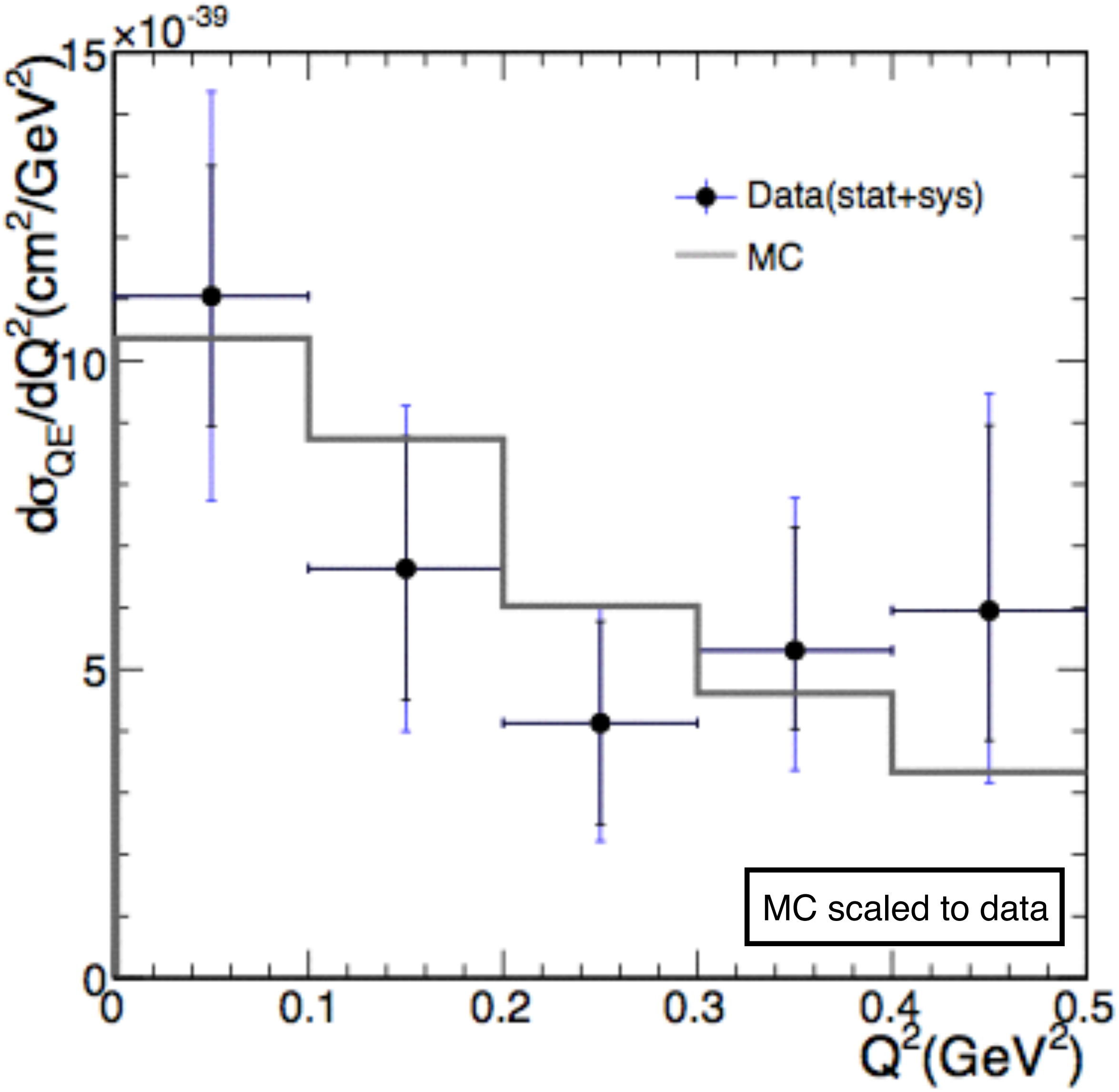
ν_μ CCQE Cross Section Results

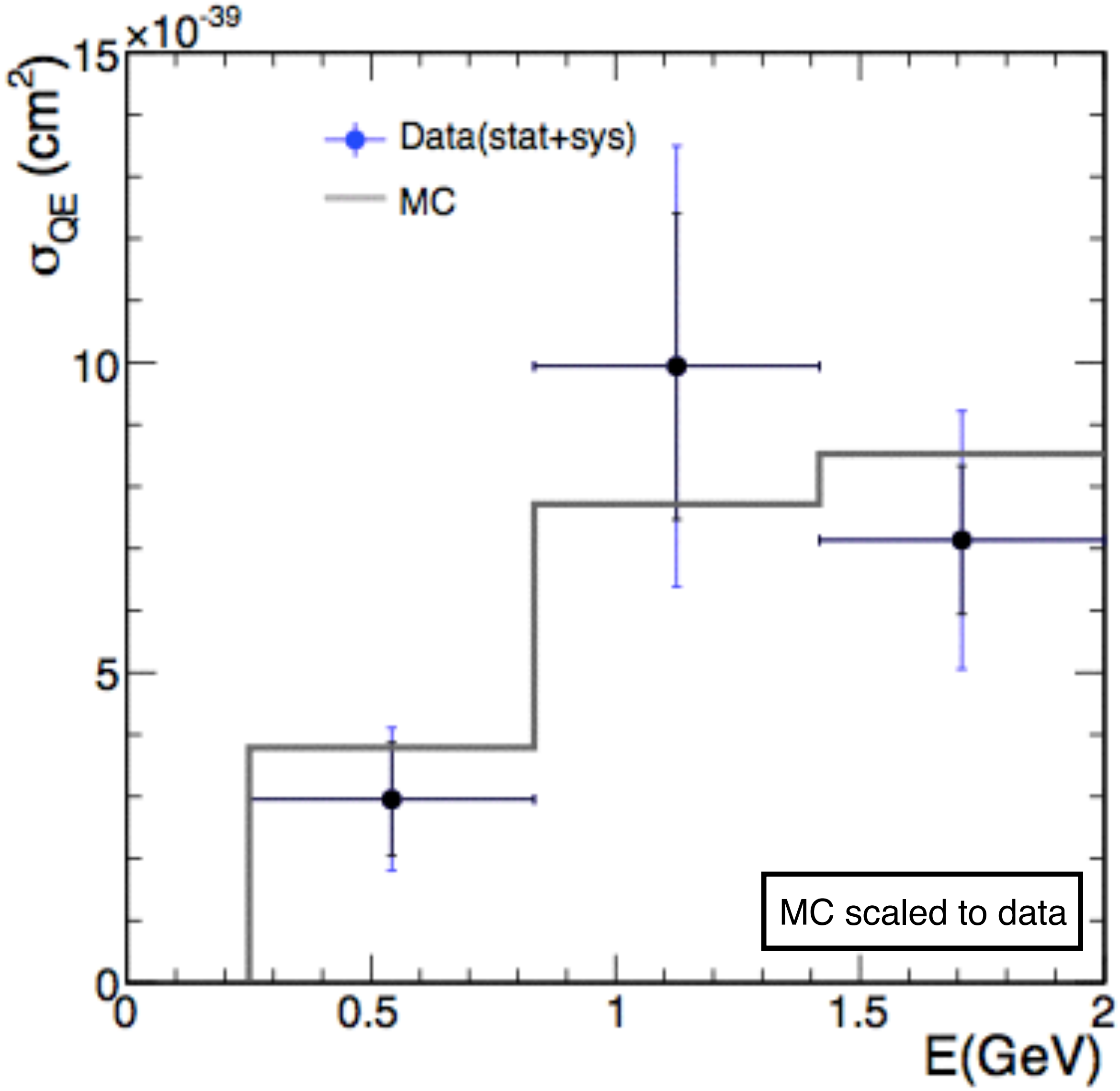




Detector resolution is accounted for through the unfolding procedure.
Efficiencies have been calculated and applied.

ν_μ CCQE Cross Section Results

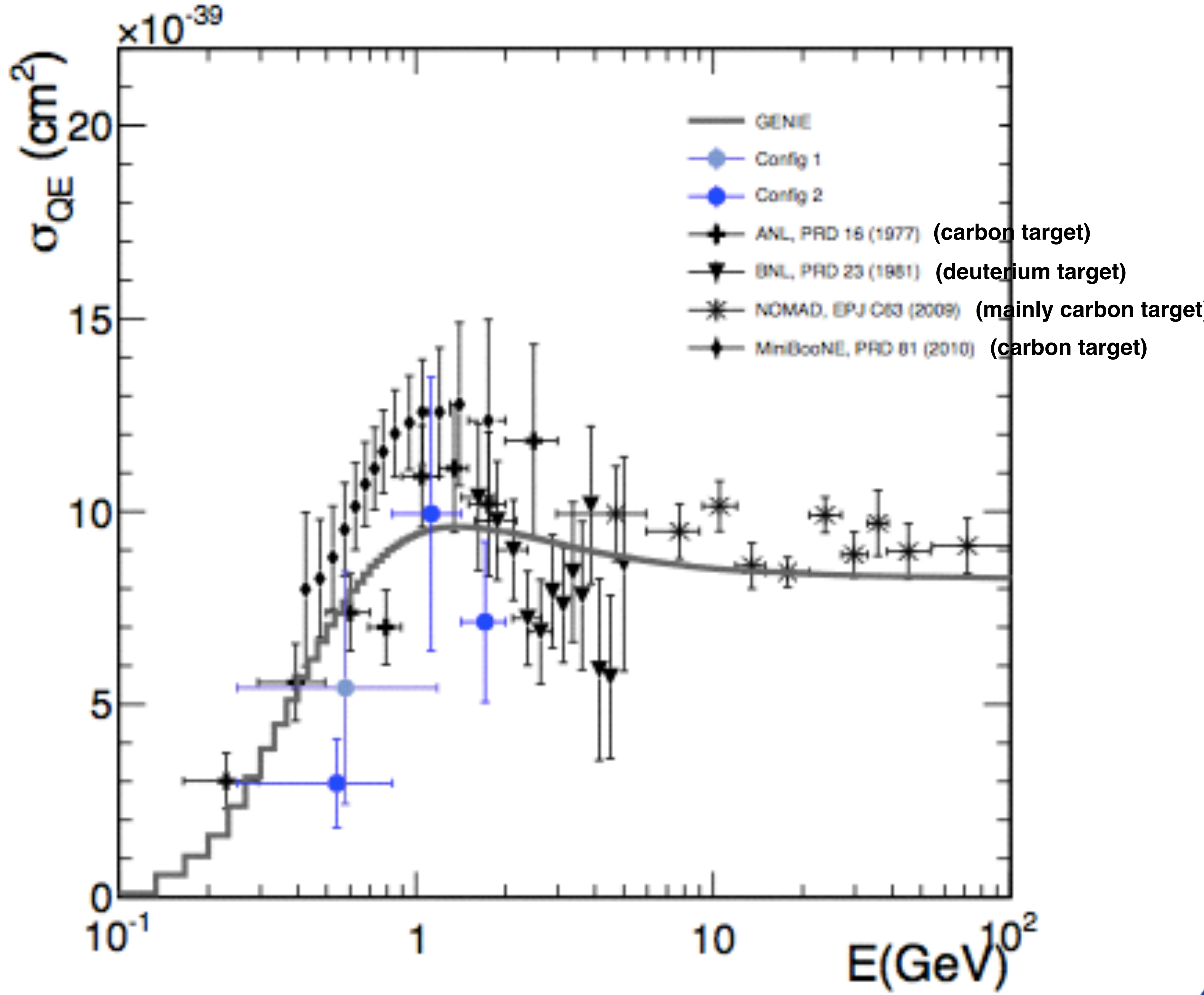




$Q^2(\mathrm{GeV}^2)$	$\frac{d\sigma}{dQ^2_{\mathrm{QE}}}\left(\frac{\mathrm{cm}^2}{\mathrm{GeV}^2}\right)$	stat	syst	total error
0-0.1	11.1×10^{-39}	2.1×10^{-39}	2.6×10^{-39}	3.3×10^{-39}
0.1-0.2	6.6×10^{-39}	2.1×10^{-39}	1.5×10^{-39}	2.6×10^{-39}
0.2-0.3	4.1×10^{-39}	1.6×10^{-39}	1.0×10^{-39}	1.9×10^{-39}
0.3-0.4	5.3×10^{-39}	2.0×10^{-39}	1.5×10^{-39}	2.5×10^{-39}
0.4-0.5	6.0×10^{-39}	3.0×10^{-39}	1.8×10^{-39}	3.5×10^{-39}

E (GeV)	$\frac{d\sigma}{dE}\left(\frac{\mathrm{cm}^2}{\mathrm{GeV}}\right)$	stat	syst	total error
0.25-0.8	3.0×10^{-39}	0.9×10^{-39}	0.7×10^{-39}	1.2×10^{-39}
0.8-1.4	9.9×10^{-39}	2.5×10^{-39}	2.5×10^{-39}	3.6×10^{-39}
1.4-2.0	7.1×10^{-39}	1.2×10^{-39}	1.7×10^{-39}	2.1×10^{-39}

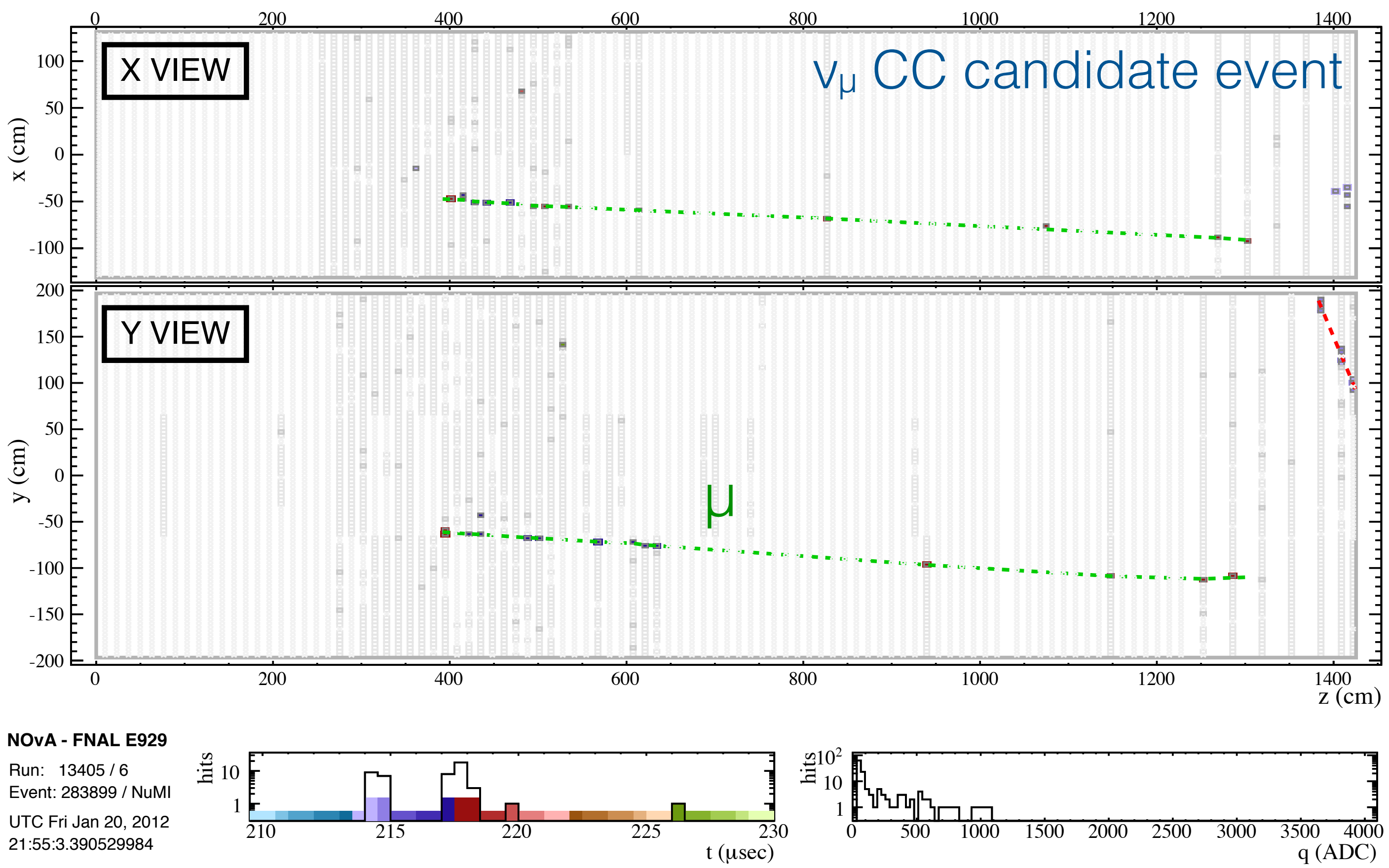
νμ CCQE Cross Section Results



Measurement of the ν_μ Charged Current (CC) Inclusive Cross Section

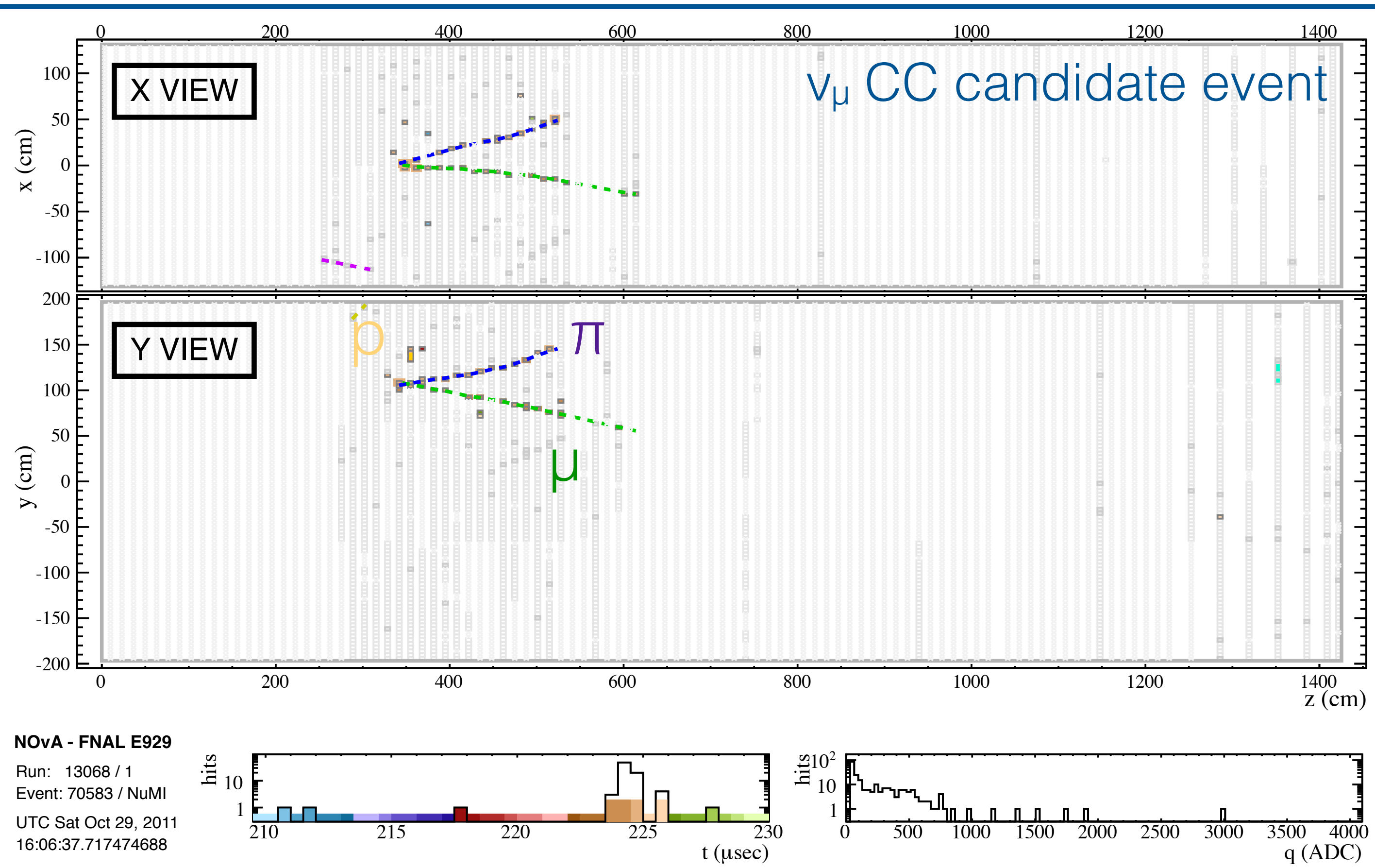
Enrique Arrieta-Diaz, Ph.D. Thesis
Michigan State University, July 2014

ν_μ CC Inclusive Event Selection



$$\nu_\mu + \mathrm{n} \longrightarrow \mu^- + \mathrm{p}$$

CCQE candidate



$$\nu_\mu + \mathrm{p} \longrightarrow \mu^- + \mathrm{p} + \pi^+$$

RES candidate

ν_μ CC Inclusive Event Selection

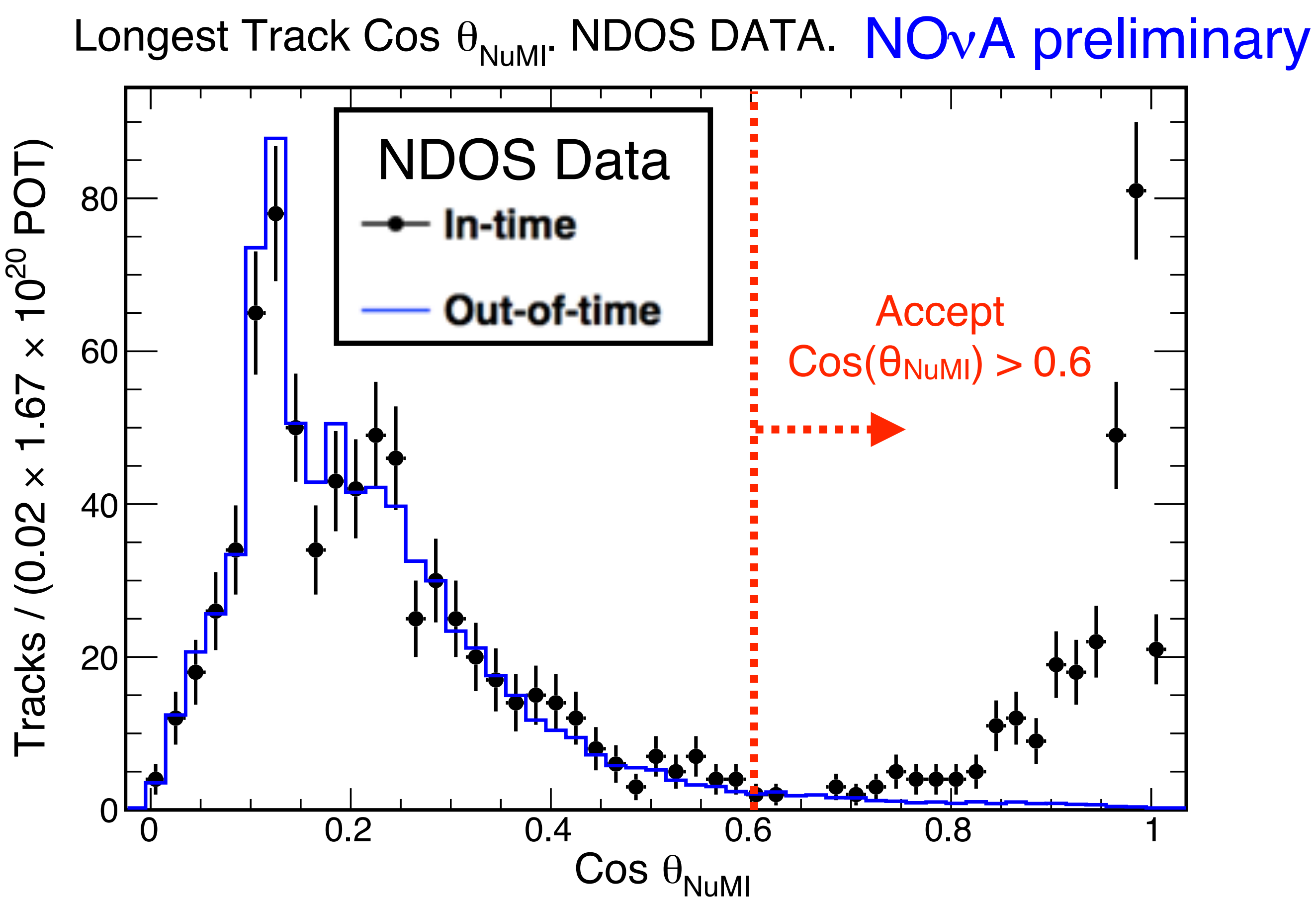
Pre-selection criteria reduce background from neutral current events and cosmic rays

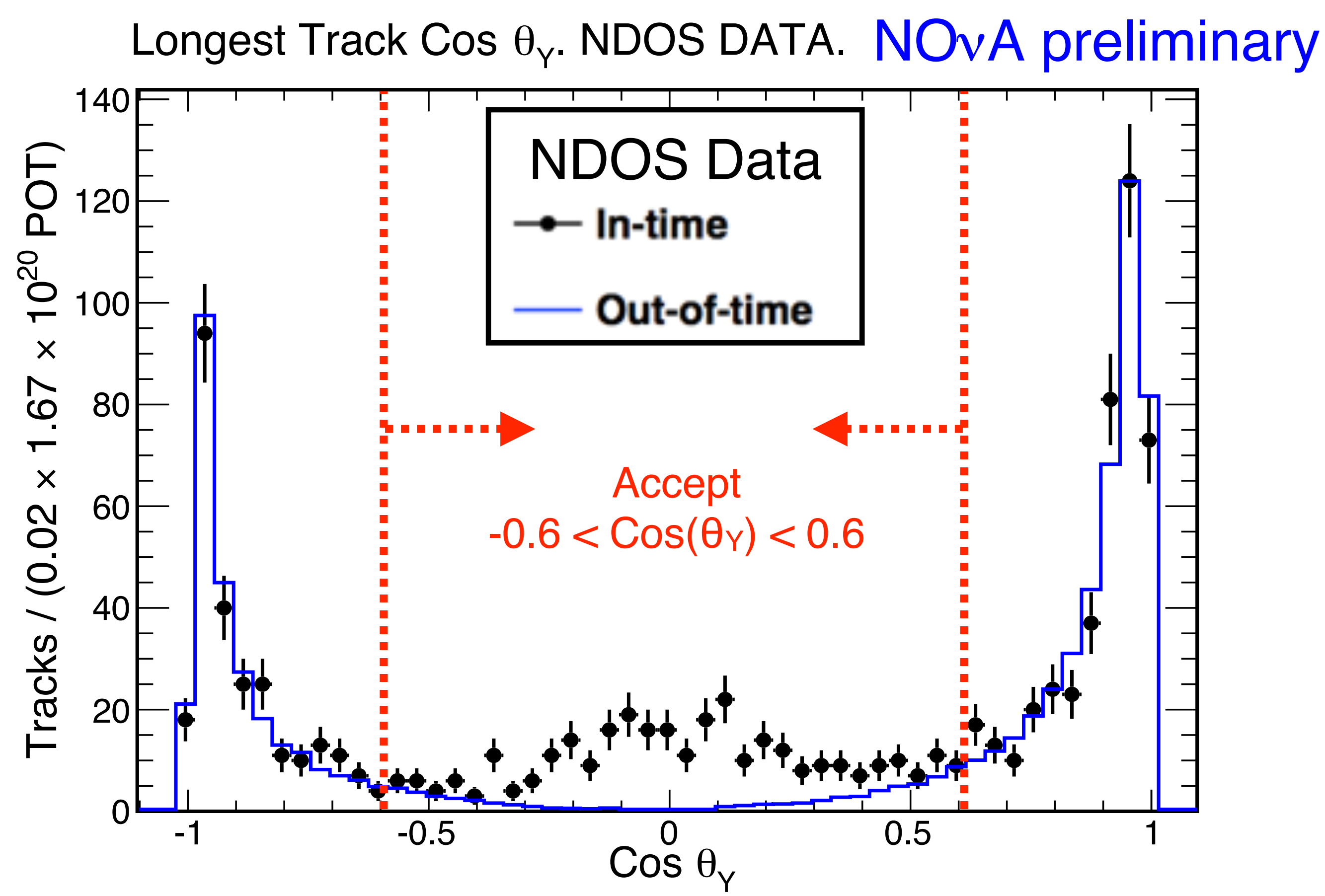
- timing within NuMI beam spill window
- **at least one** reconstructed, 3D, contained track with length greater than 200 cm (3.8% of background is then ν_μ NC)
- fiducial cuts on vertex position
- containment fiducial cuts
- cosmic cuts on longest track: $\cos(\theta_{NuMI}) > 0.6$ and $\cos(\theta_y) < 0.6$ (angle between track and vertical component of track)

cut on MIP fraction reduces EM background

- MIP defined as 1.1 MeV/cm < dE/dx < 2.7 MeV/cm
- MIP fraction for a track: n/N = # cells containing a MIP/total # cells in track
- for the longest track in the event, n/N > 0.4

ν_μ CC Inclusive - Cosmic Cut Variables for In-time versus Out-of-time Data



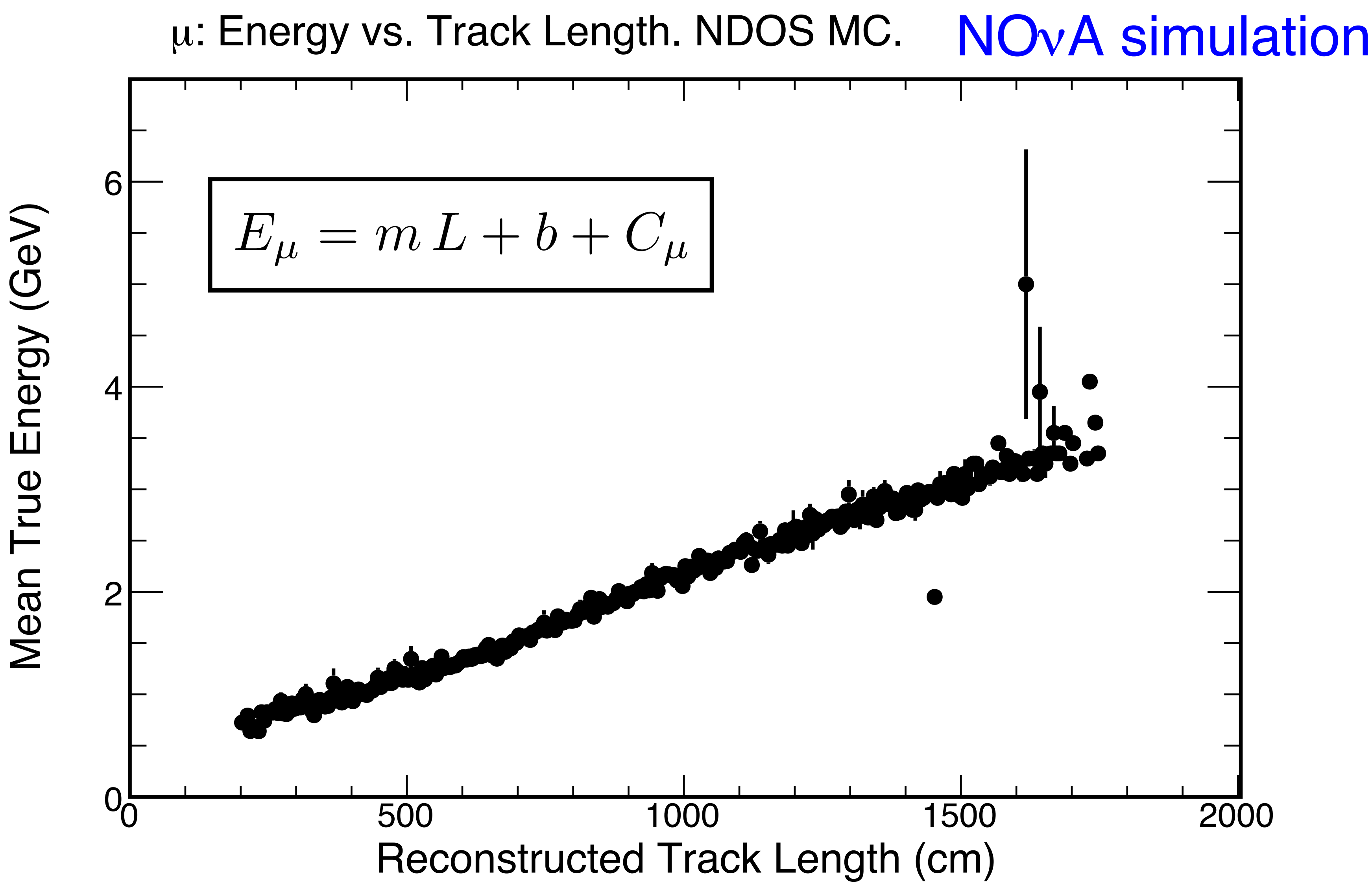


COSMIC CUTS FOR LONGEST TRACK IN EVENT:

- $\cos(\theta_{NuMI}) > 0.6$
- $\cos(\theta_y) < 0.6$ (angle between track and vertical component of track)

(in-time data include neutrino interactions as well as CR backgrounds)

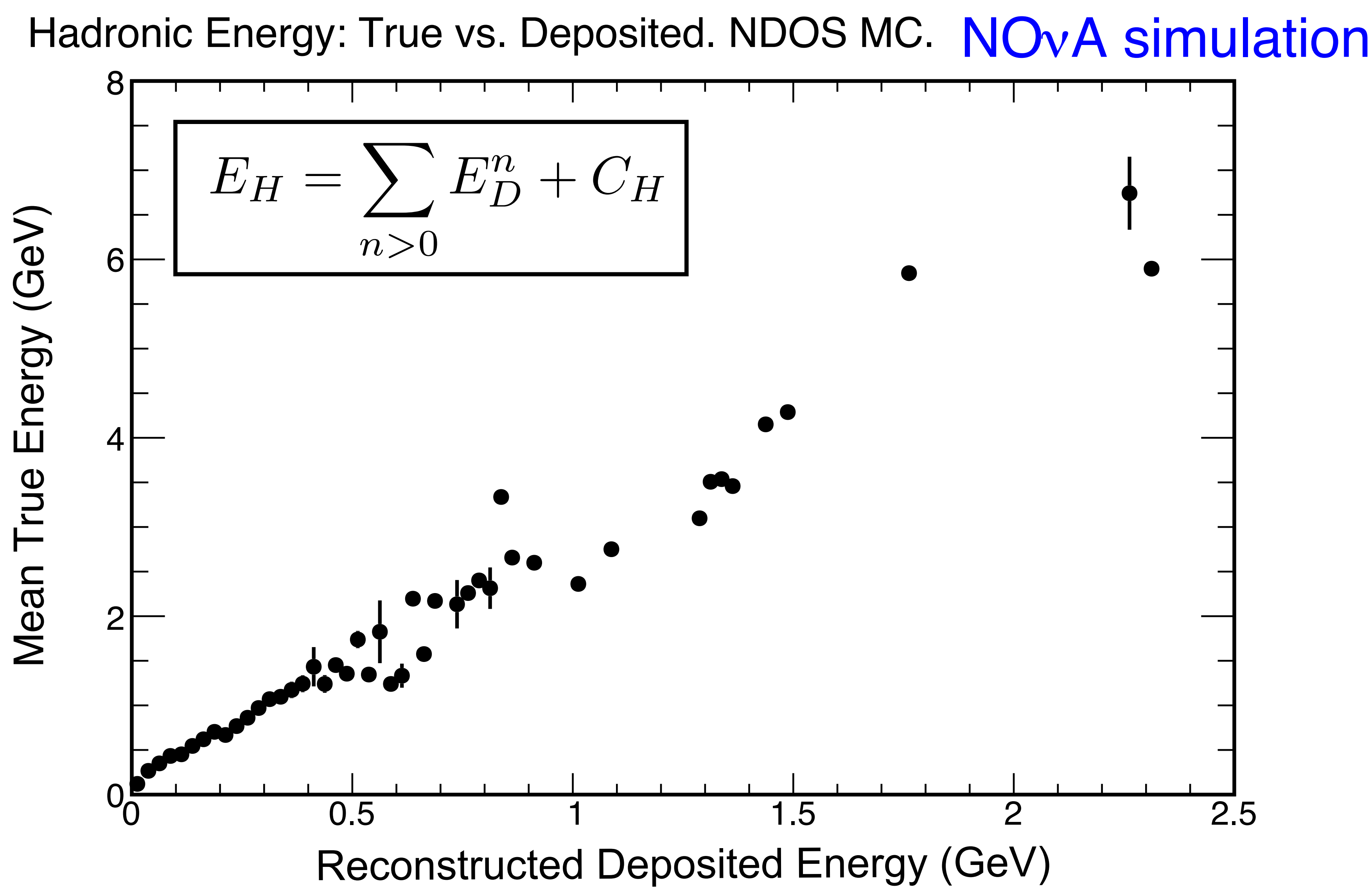
ν_μ CC Inclusive - Energy Estimation for Tracks



LINEAR FIT OF TRUE MUON ENERGY VERSUS TRACK LENGTH

- C_μ are energy-dependent corrections that achieve $\Delta E_\mu = E_{true} - E_{reco} = 0$
- muon energy resolution at 1 GeV = 14%

ν_μ CC Inclusive - Energy Estimation for Hadronic Activity

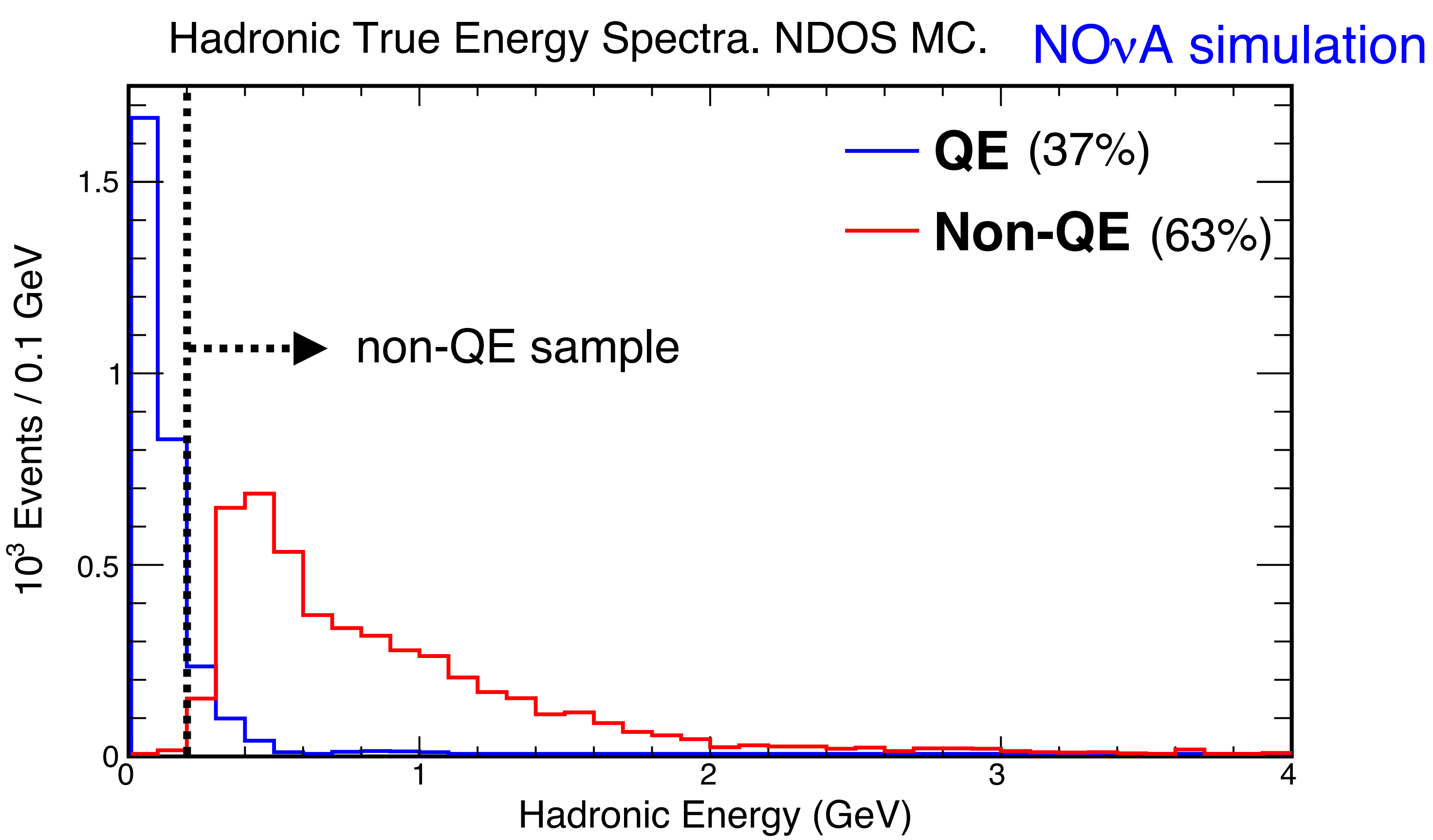


POLYNOMIAL FIT OF TRUE ENERGY VS. RECONSTRUCTED DEPOSITED ENERGY

- hadronic energy is any energy not associated with longest track
- C_H are energy-dependent corrections that achieve $\Delta E_H = E_{true} - E_{reco} = 0$
- hadronic energy resolution at 0.5 GeV = 36.5%

ν_μ CC Inclusive - Energy Estimation for Hadronic Activity QE vs. non-QE

Quasi-elastic and non-quasi-elastic events are reconstructed with different efficiencies, so they have to be treated separately in the cross section measurement.



DEFINE:

QE sample: events with E_H < 200 MeV

28% of all events

p = 63%, ϵ = 74%

E_μ resolution = 5% at 2 GeV

E_H resolution = 60 MeV

non-QE sample: events with E_H > 200 MeV

72% of all events

p = 82%, ϵ = 78%

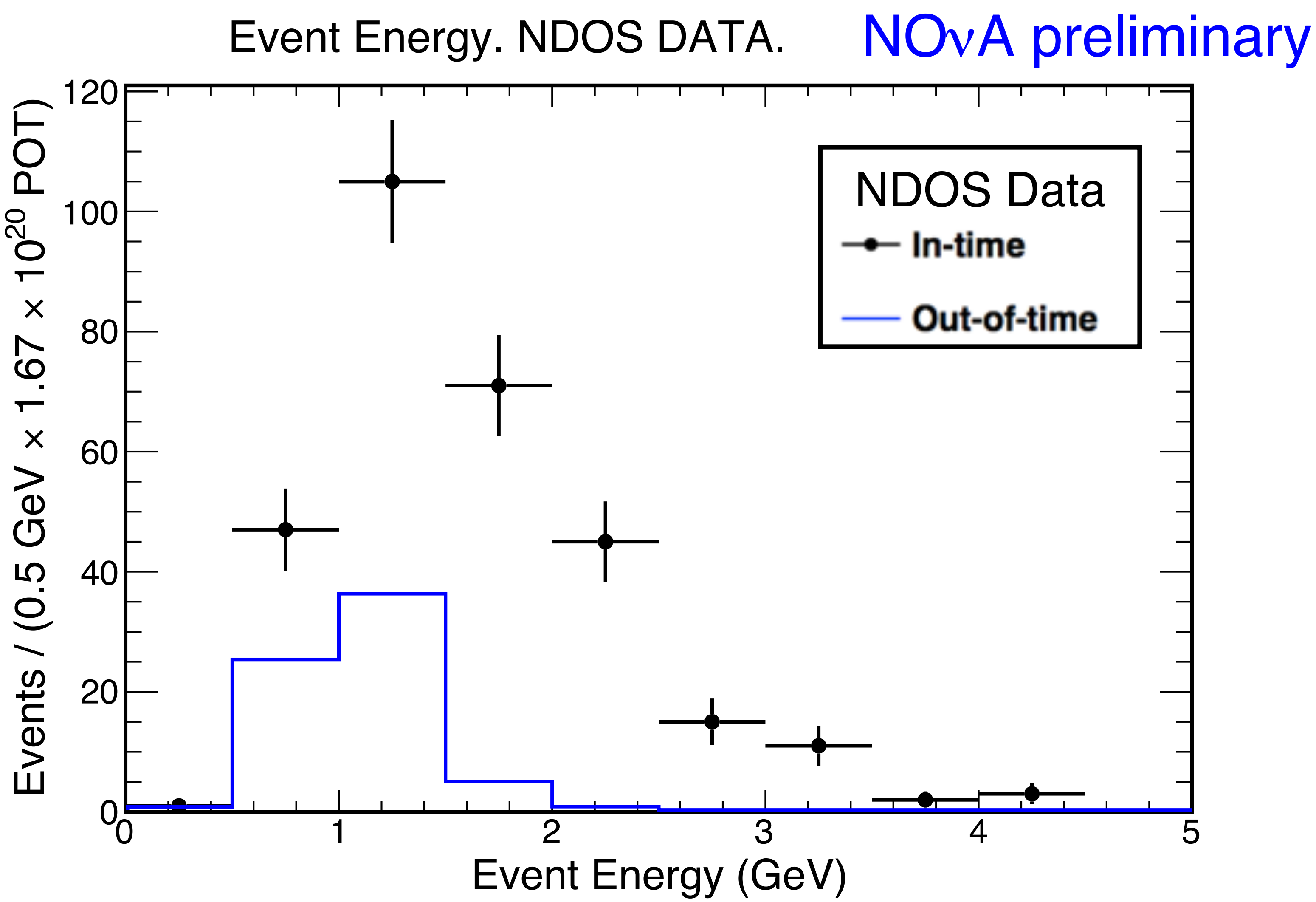
E_μ resolution = 6.5% at 2 GeV

E_H resolution = 240 MeV

84.1% of QE events have E_{trueH} < 200 MeV

99.6% of non-QE events have E_{trueH} > 200 MeV

ν_μ CC Inclusive - Cosmic Background Subtraction



All events	146085
3D cut	93722
LTL cut	54986
VR cut	3715
Containment cut	993
MIP cut	939
Cosmic cut	301

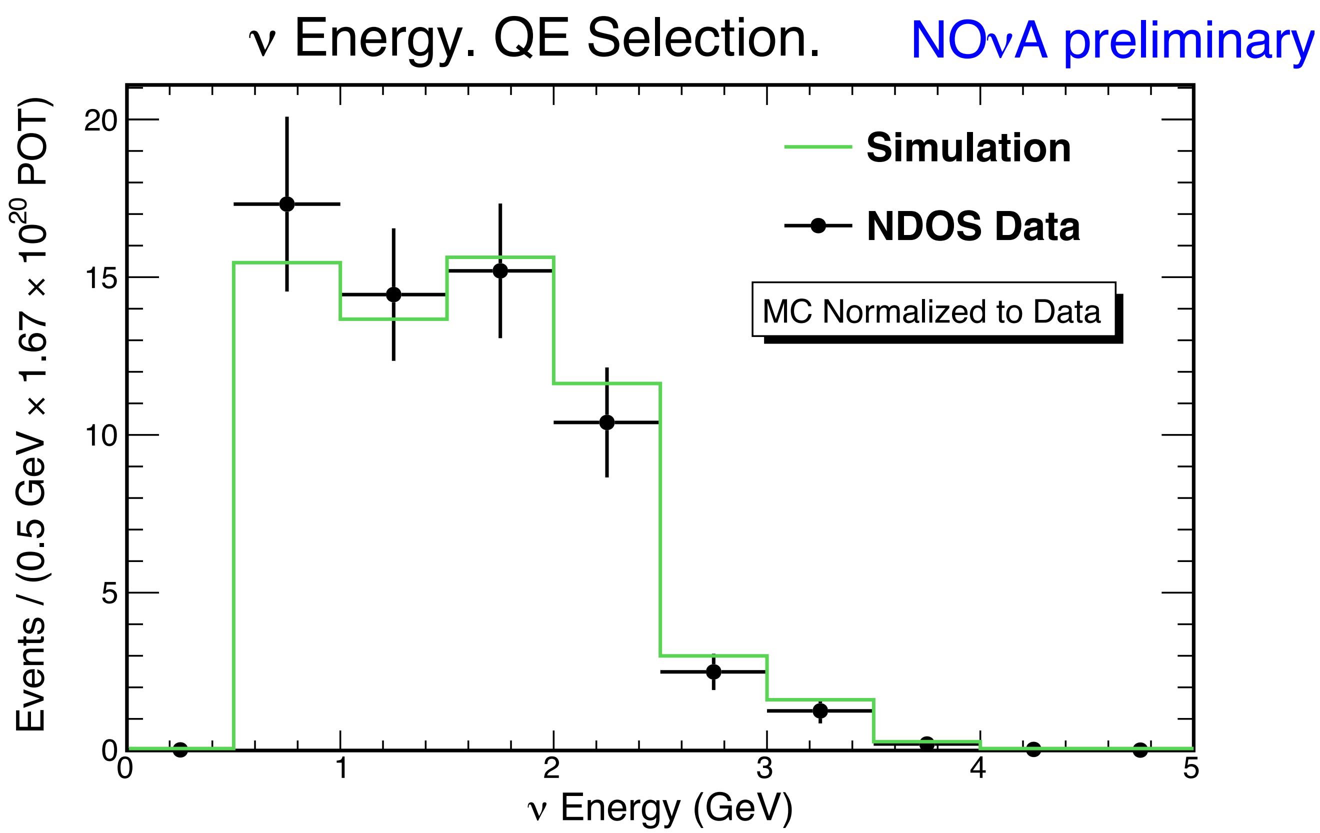
total # in-time events passing all cuts

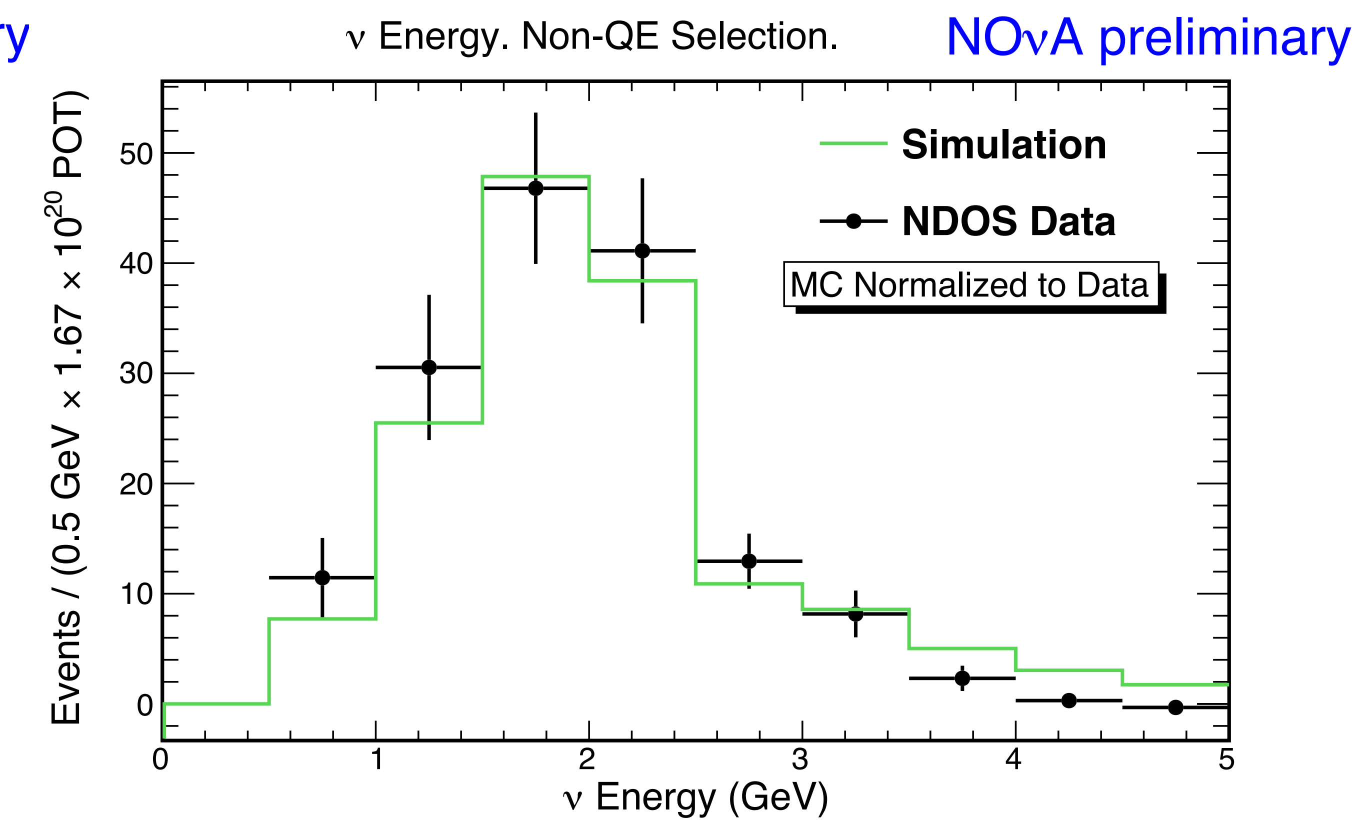
in-time and **out-of-time** data go through same event selection procedure

- 301 events from in-time data sample pass all selection cuts
- 69.5 events from out-of-time data sample pass all selection cuts

total # of ν_μ CC candidates = (in-time) - (out-of-time) = **213.5**

ν_μ CC Inclusive - Reconstruction of Neutrino Energy

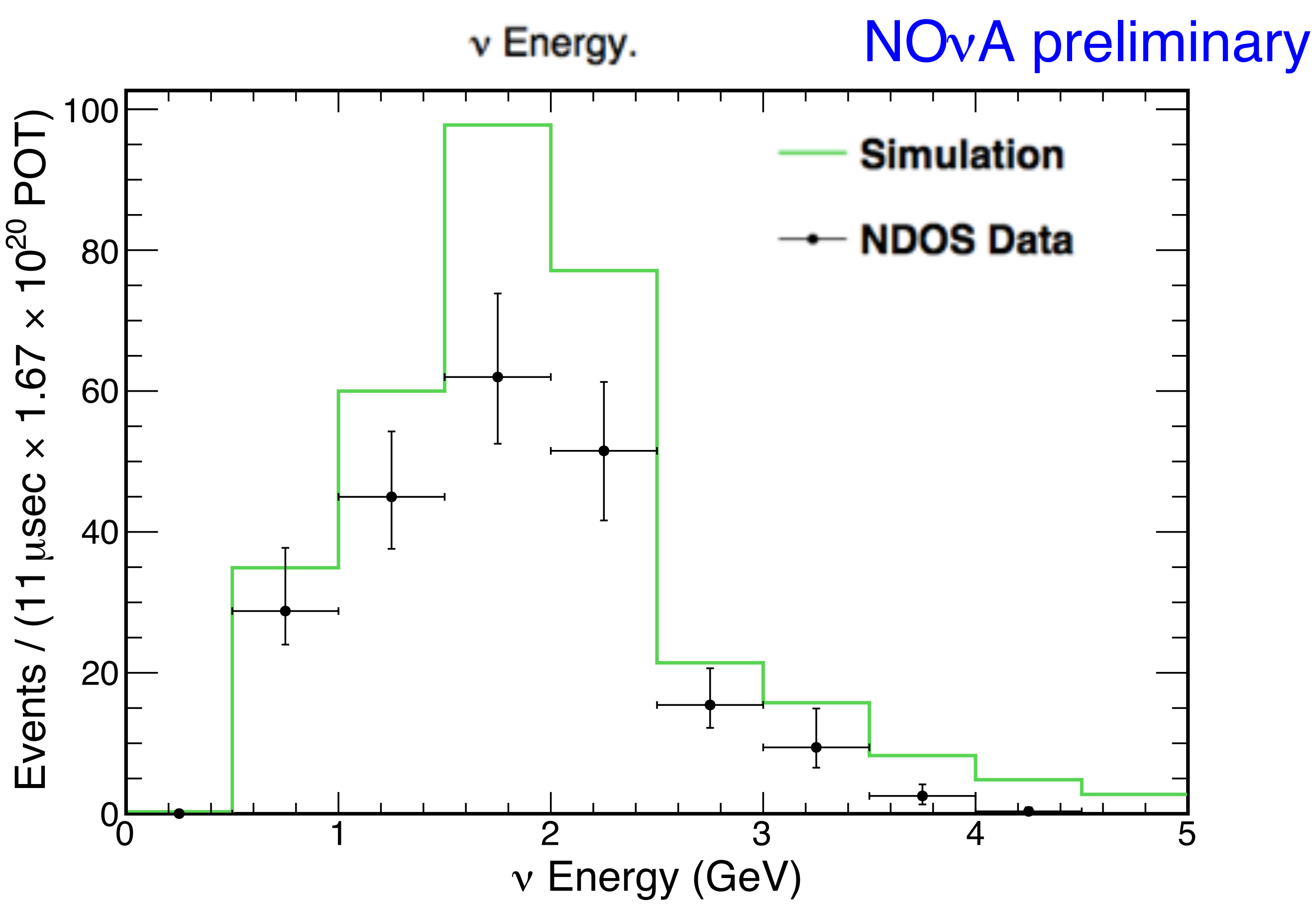


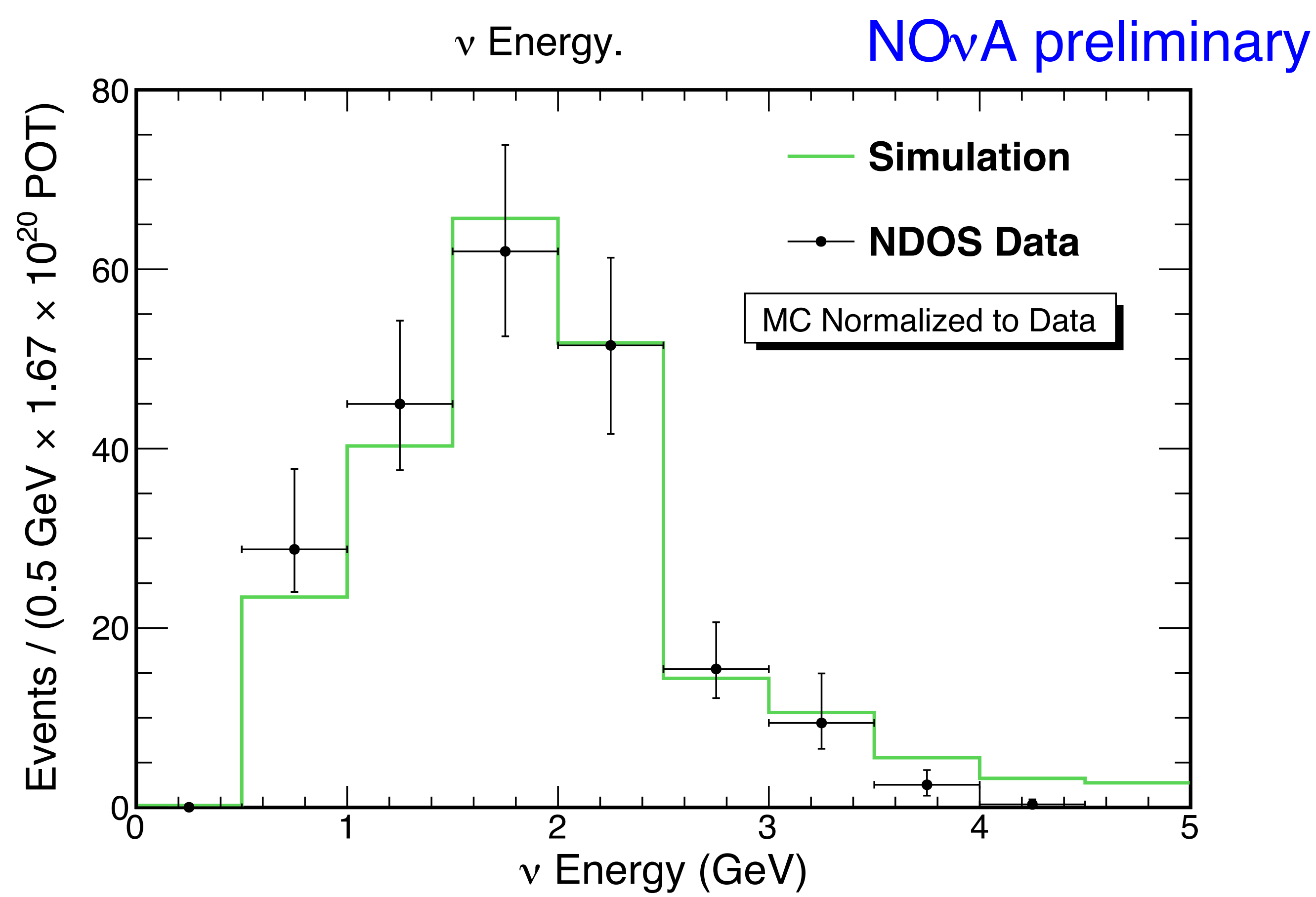


Shapes of energy distributions for data and MC show good agreement between 0.5 GeV and 4 GeV.

Data has ~35% fewer events than MC predicts for both classifications of events. A study shows that the flux of ν_μ coming from kaon decay (the dominant contribution to neutrino production for E_μ > 1.5 GeV) is ~1/3 less than that predicted by MC, so the normalization discrepancy is due to an over-estimation of the K flux in the MC.

ν_μ CC Inclusive - Reconstruction of Neutrino Energy

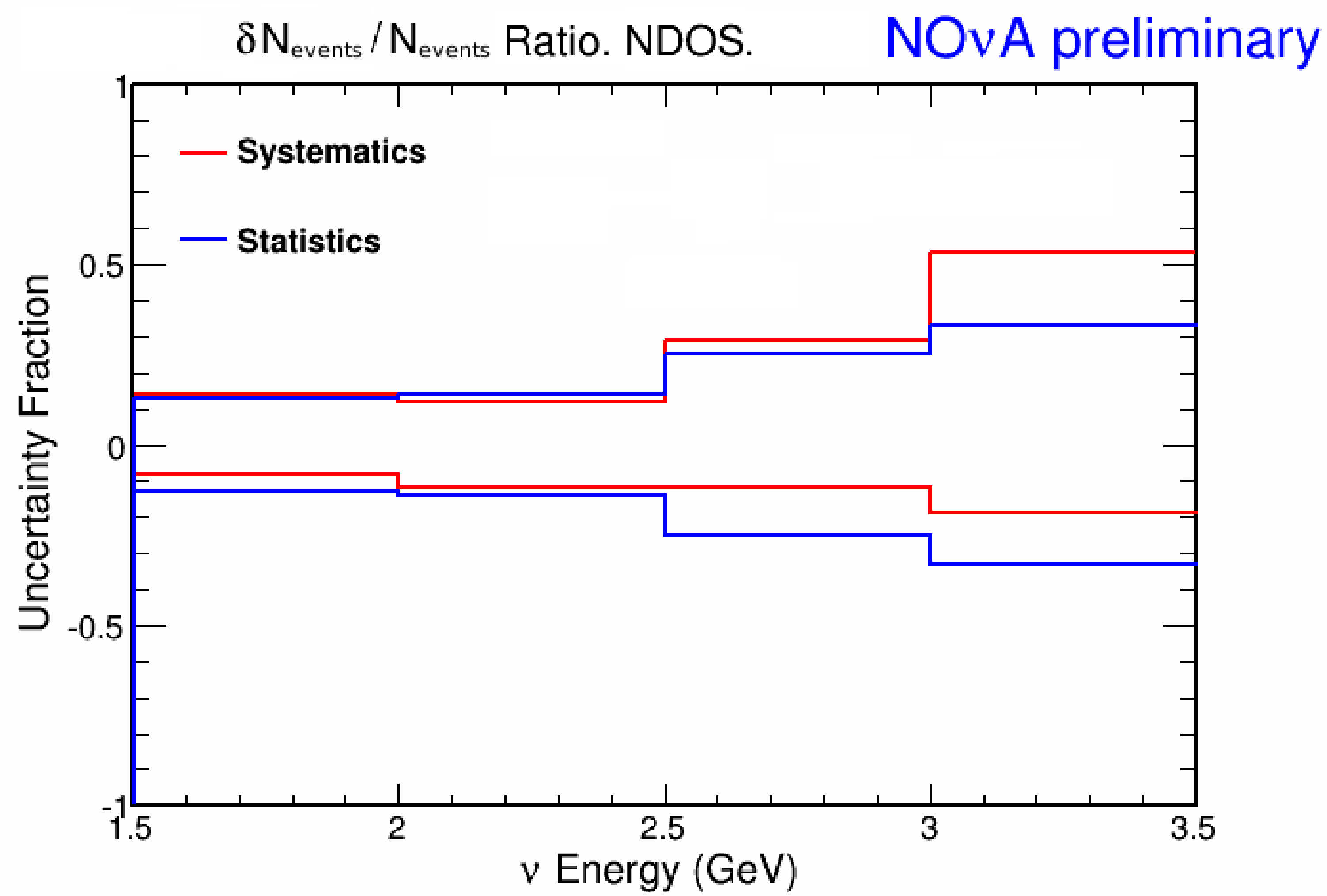




Shapes of energy distributions for data and MC show good agreement between 0.5 GeV and 4 GeV.

MC predicts 328.1 events for the 213.5 ν_μ CC candidates in the data.

ν_μ CC Inclusive - Systematic Uncertainties in Number of Events



Systematic and statistical uncertainties are comparable in the 2-2.5 GeV range where most of the events are located.

Modeling of Neutrino Interactions in the Detector - ~20% at energies of interest

- uncertainties in background components and in neutrino interaction cross sections were calculated using GENIE reweighing tools

Detector Performance Uncertainties - ~15% at energies of interest

- due to any difference between actual bad channels for a data run and the bad channel map used in MC, calculated by varying the channel configurations

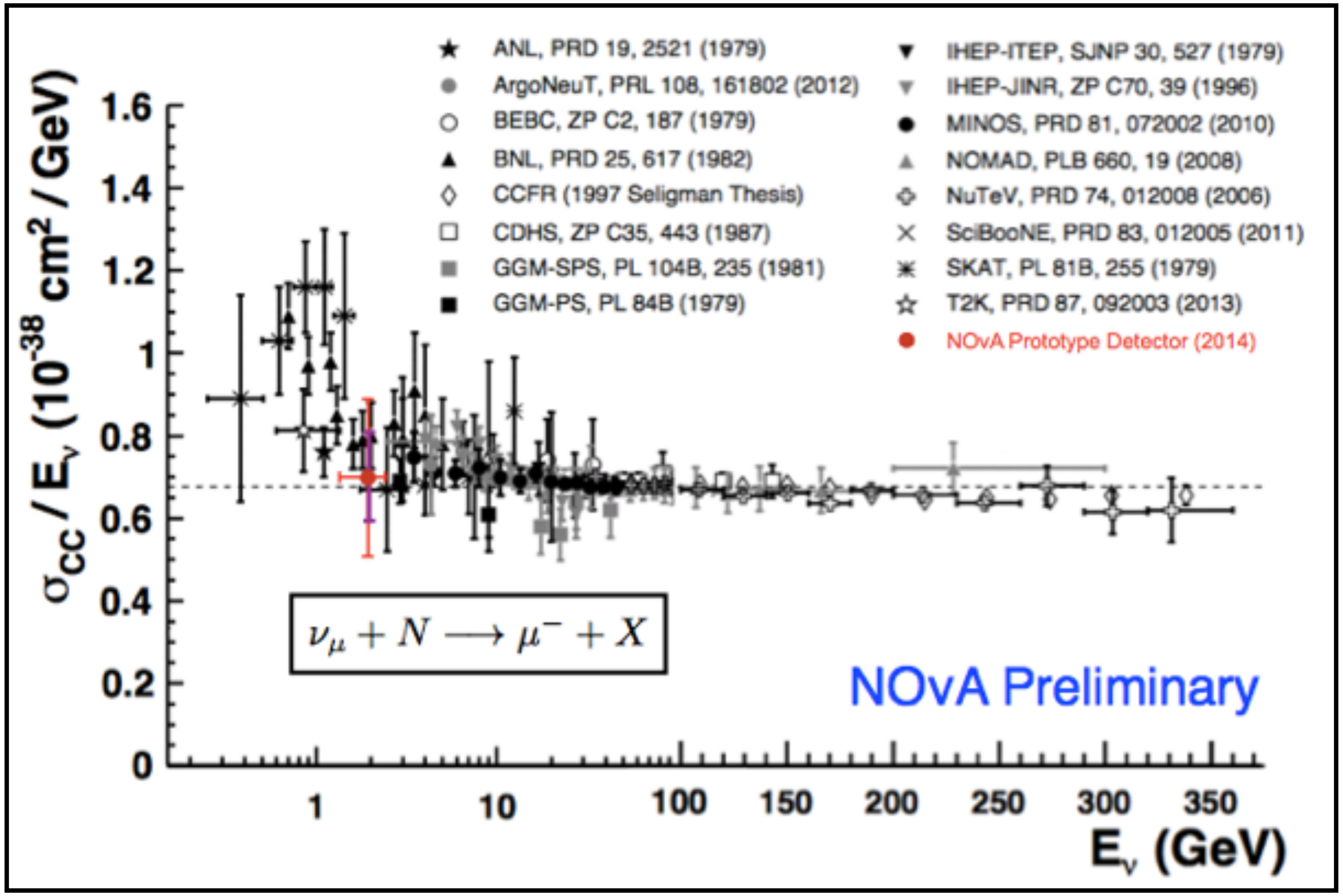
ν_μ Energy Uncertainty - ~10% at energies of interest

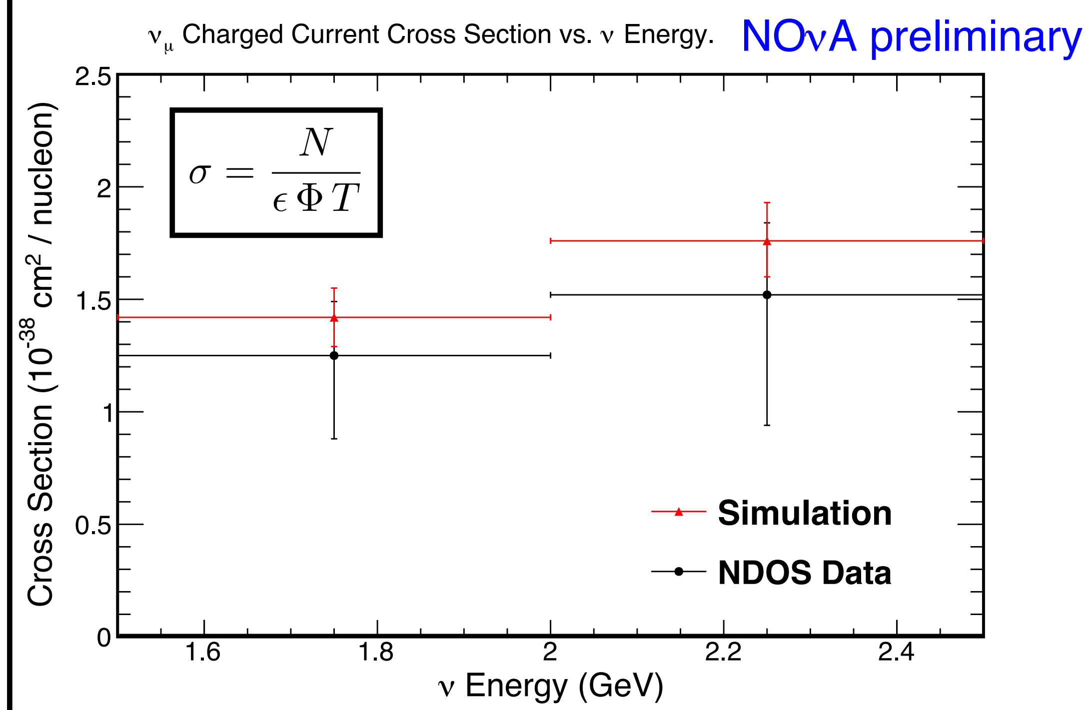
- calculated from uncertainty in measured track lengths and dE/dx of tracks

Unfolding Uncertainty - ~5% at energies of interest

- calculated using the initial and final iterations of the unfolding algorithm as well as by varying the cross section model and axial mass used

ν_μ CC Inclusive Cross Section Results





Plot taken from J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012) and 2013 partial update for the 2014 edition

$$\sigma_{data} = (1.389 \pm 0.219 \text{ stat } {}^{+0.330}_{-0.383} \text{ sys }) \times 10^{-38} cm^2$$ at 1.97 GeV

Measurement is in agreement with previous measurements made by BNL and SciBooNE.

Summary

- The NOvA prototype detector has been taking data 6.1° off-axis of the NuMI beamline since November 2011.
- Two detector configurations were realized. Data corresponding to a total of ~1.8 x 10^{20} POT were collected.
- Measurements of the ν_μ CCQE and ν_μ CC inclusive cross sections as a function of energy have been made. These span the energy range between 0.6 GeV and 2 GeV and agree with previous measurements from ANL, BNL, MiniBooNE, …
- The NOvA Near Detector is now complete (as of August 15th) and taking data 14 mrad off-axis of the NuMI beam. The off-axis positioning results in a neutrino spectrum that is sharply peaked around 2 GeV and a flux at that energy that is higher than for on-axis. Cross section measurements are some of the many possible measurements to be made.

For more Information on NOvA

see talks by

- Xuebing Bu (60), "The NOvA Experiment"
- Nicholas Raddatz (85), "Event and Energy Reconstruction in NOvA"

see posters by

- Susan Lein, "Energy Estimation for the NOvA ν_μ Disappearance Analysis"
- Nicholas Raddatz, "Event Selection for the NOvA ν_μ Disappearance Analysis"