NOvA Experiment

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9th Particle Physics Phenomenology Workshop
Chungli Taiwan May 3-6 , 2011

The NOvA Experiment

Two detector, long-baseline neutrino oscillation experiment

- Off-axis neutrinos from NuMI beam
- L/E~400 km/GeV, atmospheric Δm^2

Physics goals:

- Search for $\nu_\mu \rightarrow \nu_e$ transitions
- measure/limit θ_{13}
- determine mass hierarchy
- constrain CP violating phase (δ)
- precise measurements of $|\Delta m^2|$, θ_{23}
- compare neutrino/antineutrino oscillations

Neutrino Mass & Mixing

Mass eigenstates ≠ flavor eigenstates
Flavor states: creation & detection
Mass states: propagation

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j} e^{-i \frac{m_j^2 L}{2E}} U_{\beta j} \right|^2$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \mathbf{U}^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric/accelerator — Unobserved — solar/reactor

$|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ ev^2 [1]
$0.407 < \sin^2\theta_{23} < 0.583$ (90%CL) [2]

[1] P.Adamson, *et al.*, Phys.Rev.Lett. 181801(2011) (MINOS Collaboration)
[2] R.Wendell, *et al.*, Phys.Rev.**D81**,092004(2010)

$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}$ ev^2
$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$

A.Gando, *et al.*, Phys.Rev.**D83** 052002(2011) (KamLAND Collaboration)

Why measure all these angles?

Precise measurements provide valuable check that neutrino oscillations are the solution to neutrino anomalies

PMNS matrix analogous to CKM matrix

- lepton sector mixing much larger than quark sector mixing
- θ_{23} maximal, θ_{12} moderately large, θ_{13} small, zero?—why?
- Is there CP violation in the lepton sector?
- If so, is CP violation big enough to account for matter vs. antimatter asymmetry in the Universe?

Small neutrino mass suggests a heavy partner (see-saw mechanism)—

ν_e Appearance

At L/E~400 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i\left(\Delta m^2_{32} + \delta_{CP}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P_{sol} \approx \cos^2\theta_{23} \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

"Atmospheric" term depends on Δm^2_{31} and unknown θ_{13}

"Solar" term <1% for current accelerator experiments

ν_e Appearance

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$$2\sqrt{P_{atm} P_{sol}} \left[\cos\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\delta_{CP} \mp \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\delta_{CP} \right]$$

Interference Term
- for neutrinos
+ for antineutrinos

if $\delta_{CP} \neq 0$,

$$P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

ν_e Appearance

In matter, additional term in Hamiltonian from ν_e+e CC scattering modifies oscillation probability, ~30% effect in NOvA

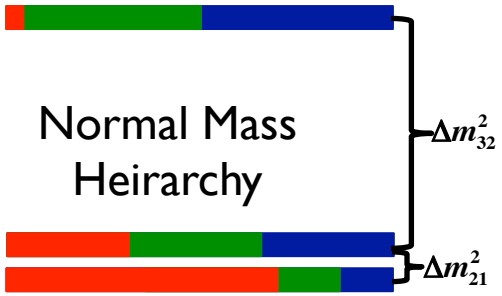
$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i(\Delta m^2_{32} + \delta_{CP})} + \sqrt{P_{sol}} \right|^2$$

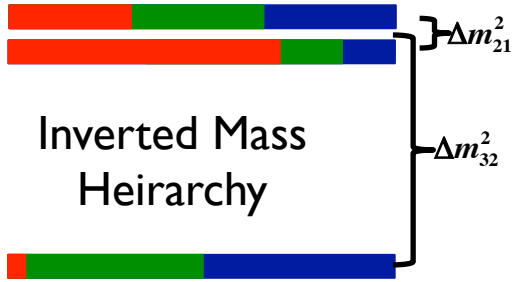
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \left[\frac{\frac{\Delta m^2_{31} L}{4E}}{\frac{\Delta m^2_{31} L}{4E} - aL}\right]^2$$

$$P_{sol} \approx \cos^2\theta_{23} \sin^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \left[\frac{\frac{\Delta m^2_{21}}{4E}}{aL}\right]^2$$

Oscillation probability depends on sign of Δm_{31}^2

$$a = \pm \frac{G_F N_e}{\sqrt{2}} \approx (4000 \text{ km})^{-1}$$





ν_e Appearance

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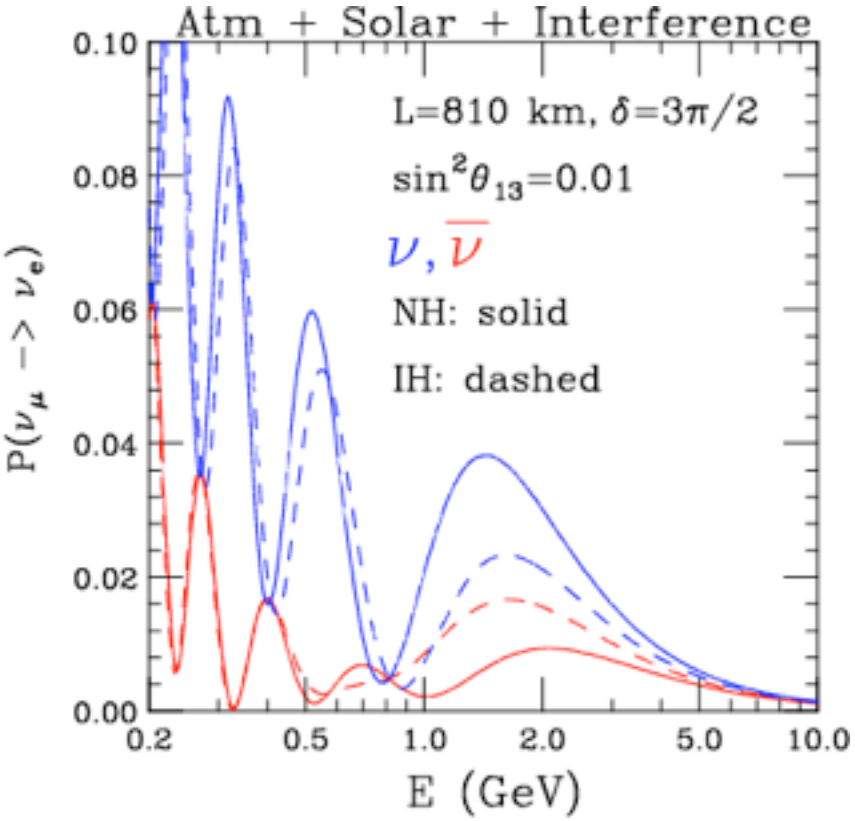
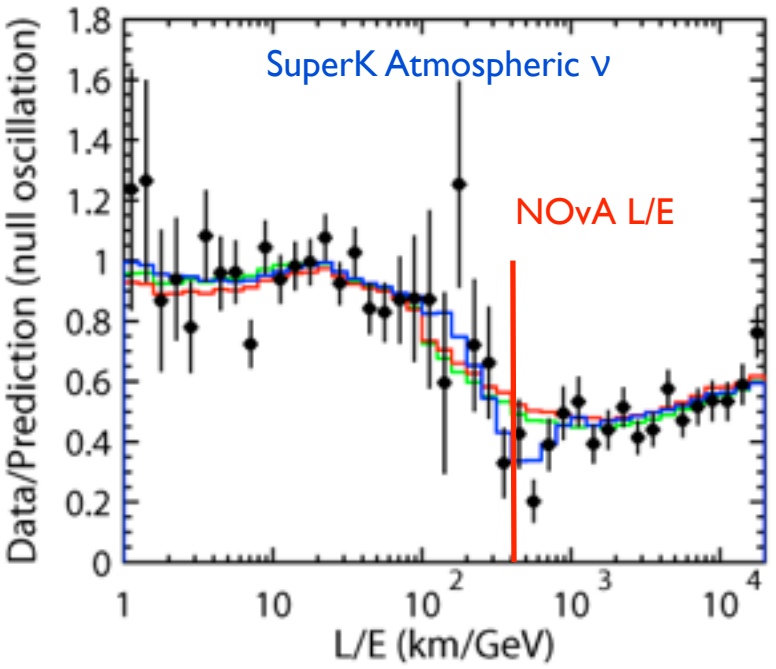


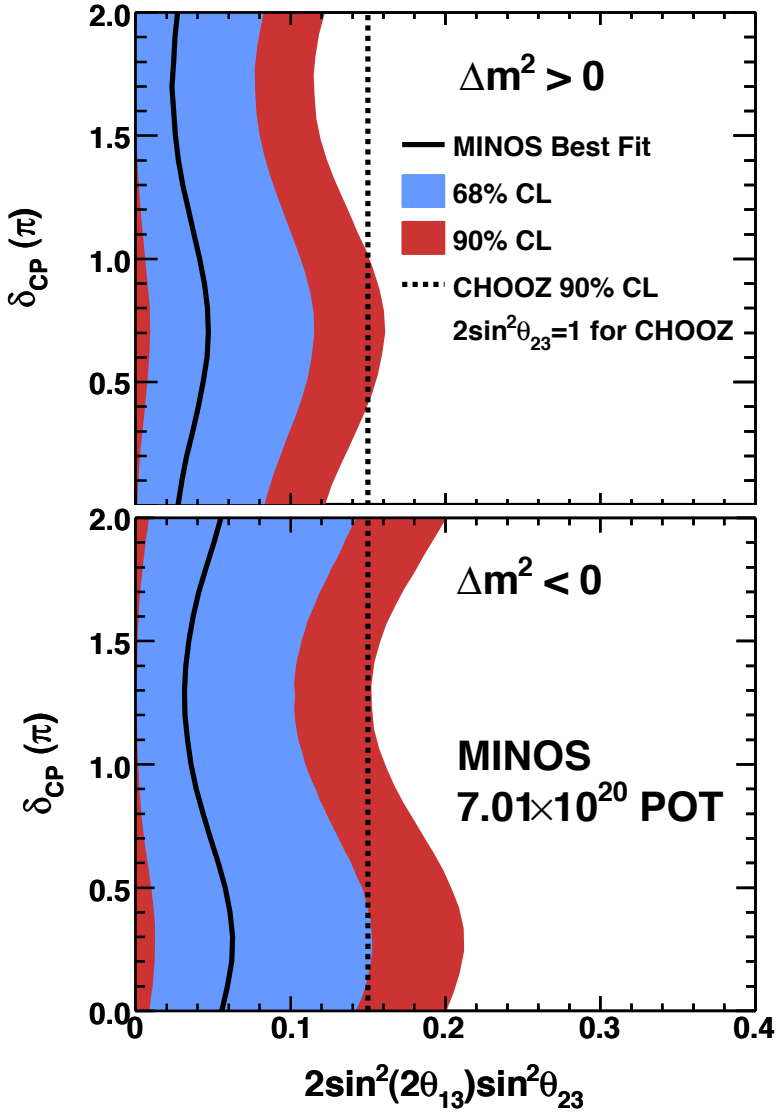


From S. Parke, "Neutrino Oscillation Phenomenology" in Neutrino Oscillations: Present Status and Future Plans

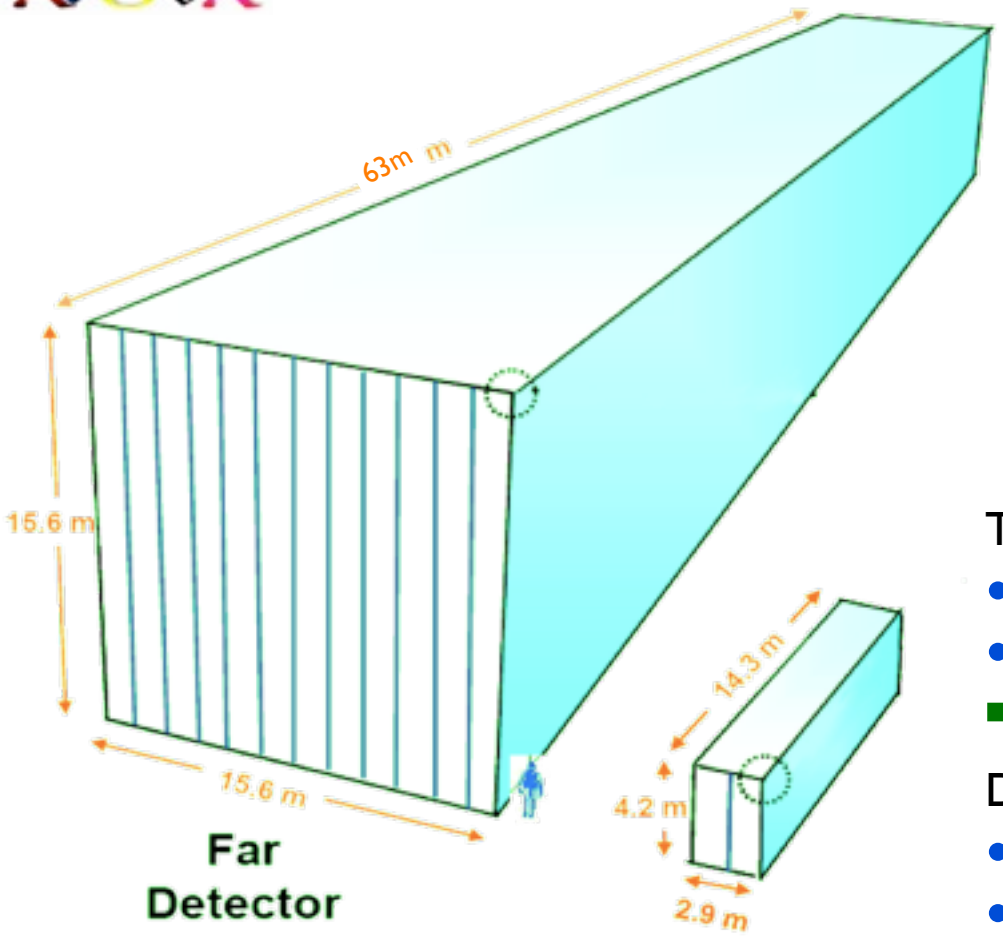
Current Limits

NOvA aims to improve limits by an order of magnitude

- bigger far detector (14 kton)
- low Z, 65% active detector for improved e and γ recognition
- Upgrade MINOS beam from 320kW to 700kW
- off-axis technique (narrow band beam)



NOvA Detectors

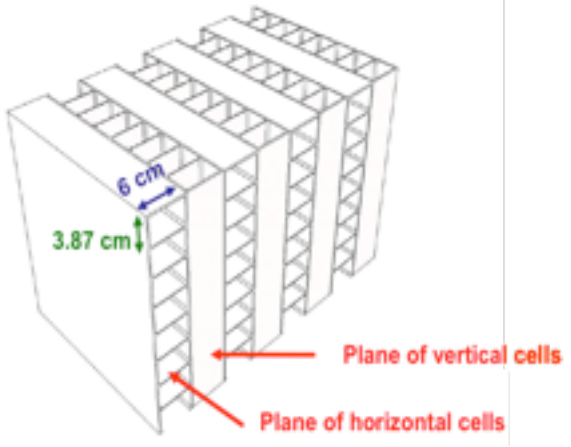


Far Detector

14 kton detector
810 km from source

Near Detector

220 ton detector
~1 km from source



Two Detector Experiment

- Measure un-oscillated and oscillated beam
- Same detector technology

➡ Reduce systematic uncertainties

Detector Structure

- Fine segmented tracking calorimeter
- Alternating horiz/vert layers
- Filled with liquid scintillator
- Low Z ($0.15X_0$ per layer)

➡ Separate e and γ from $\pi^0 \rightarrow \gamma\gamma$

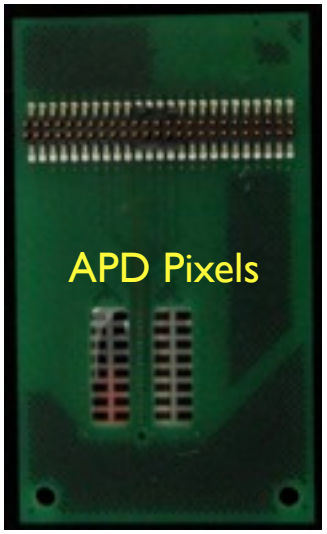
Detector Structure

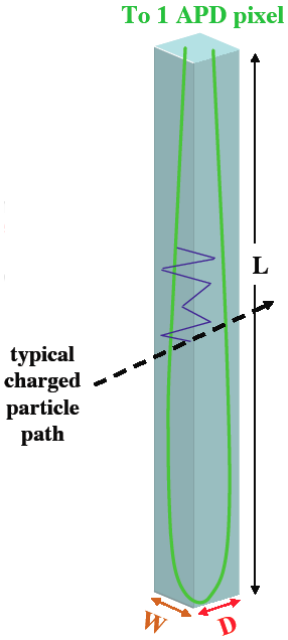
Detector Structure:

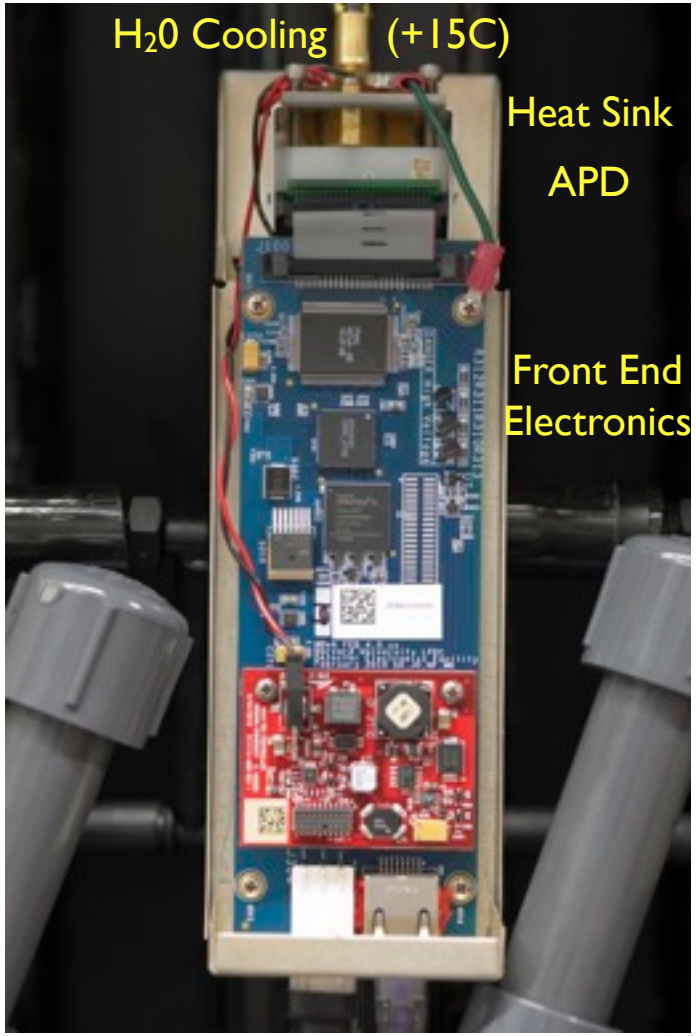
- Extruded polyvinyl cloride (PVC)
- 6.0cm x 3.9cm x 1,560cm cell
- 32cells/module
- 12 modules/plane
- 32 planes/block
- 30 blocks

Detection Technology

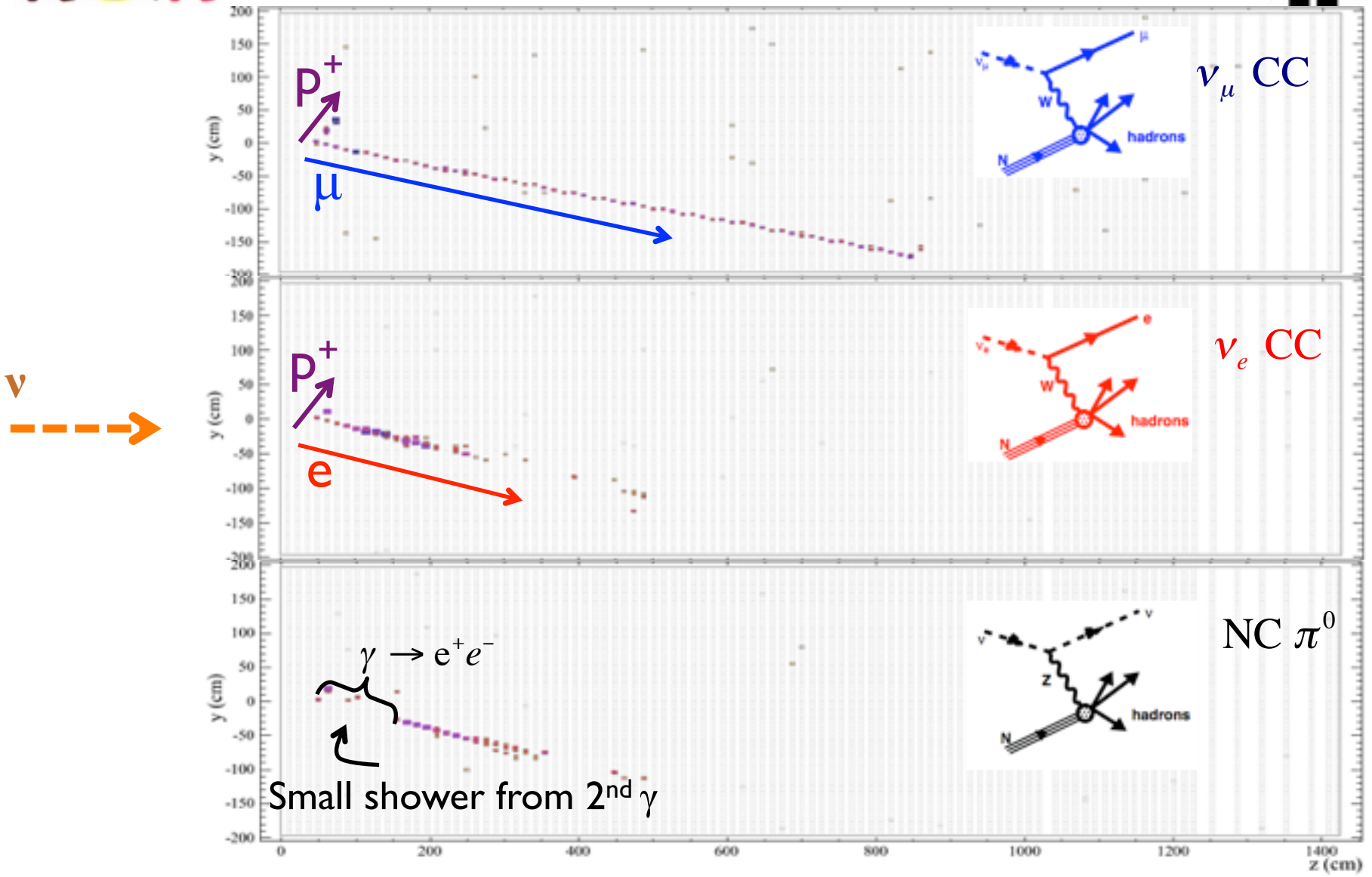
- Liquid scintillator
  - 95% mineral oil
  - 5% pseudocumene
- Wave length shifting (WLS) fiber
- Avalanche photodiode (APD) photosensor (-15C, gain ~ 100)
- Custom electronics readout



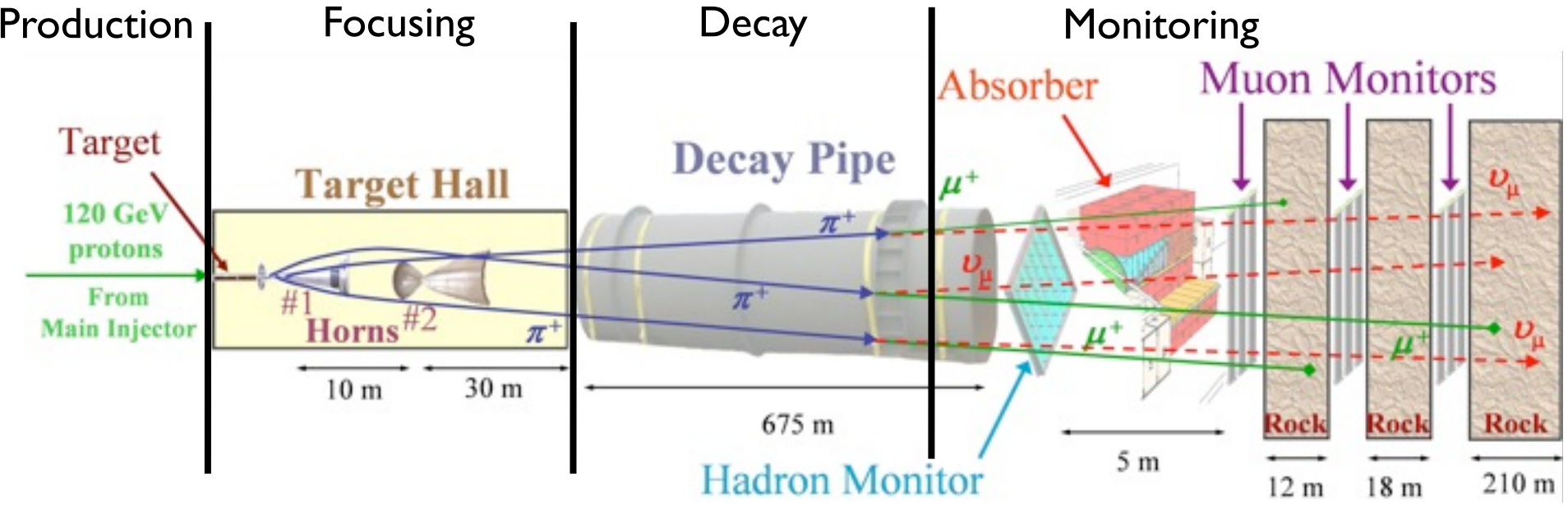




Events in NOvA (Monte Carlo)



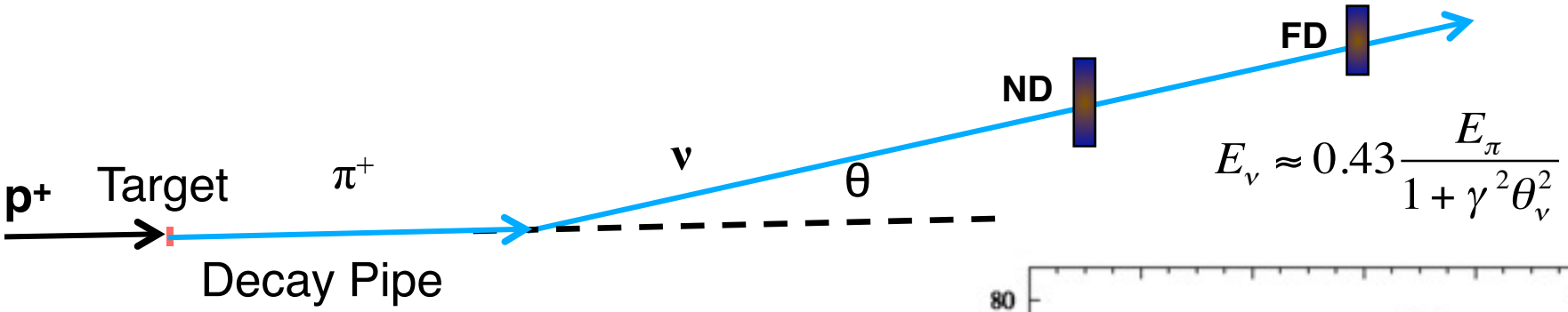
Making a Neutrino Beam



Enhanced 700kW NuMI beam line

- Cycle time from 2.2 s to 1.3 s using Recycler slip-stacking
- Increased intensity: 12 Booster batches up from 11
- New high power target
- New horn, reconfigured for higher energy beam

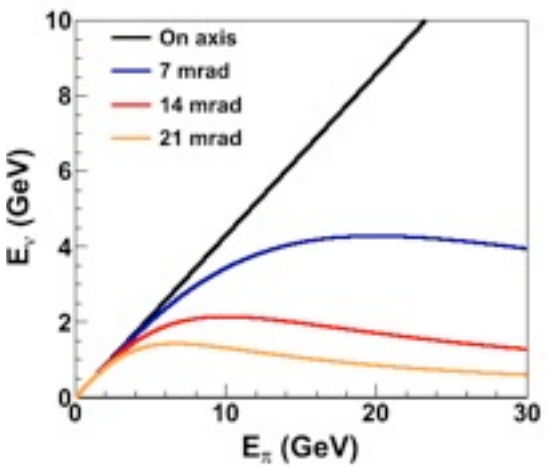
Off-axis Beam

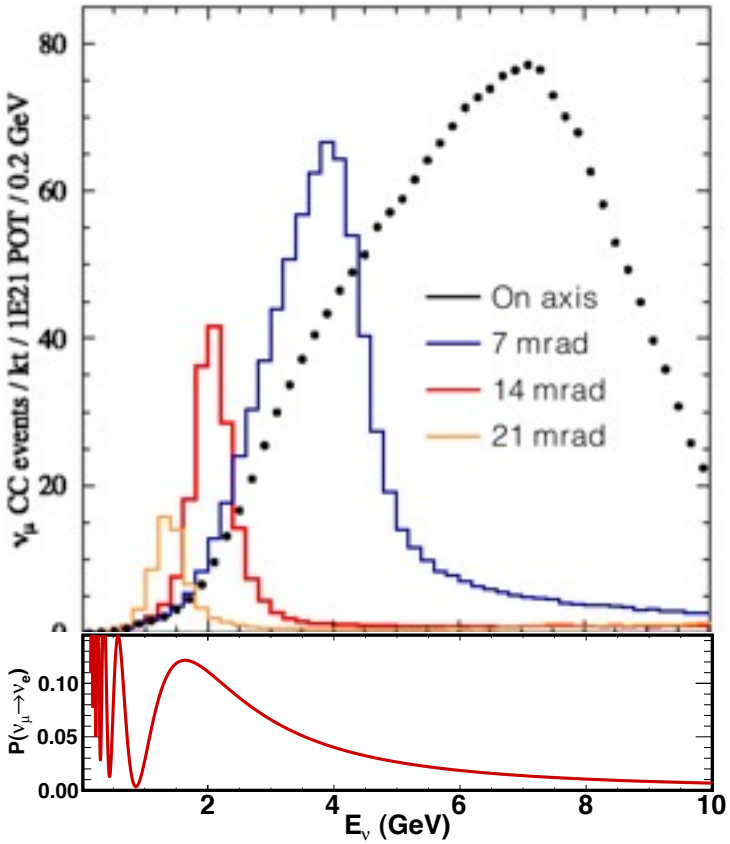


$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

At 14 mrad off-axis, narrow band beam peaked at 2 GeV

- Near oscillation maximum
- Few high energy NC background events

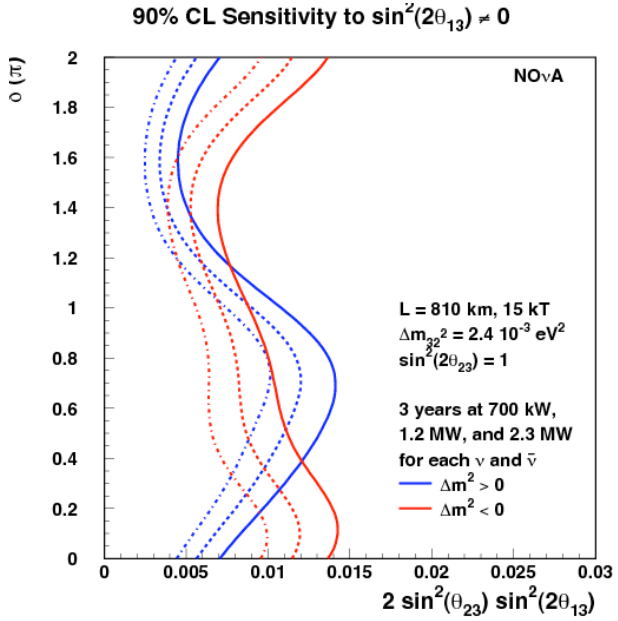


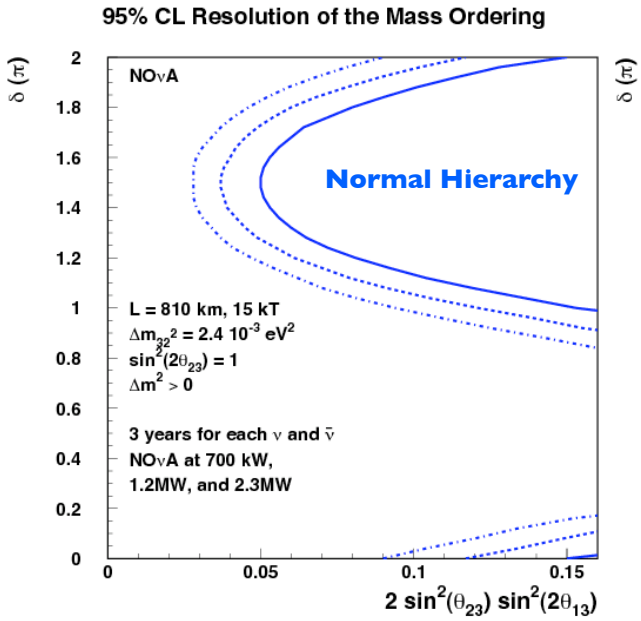


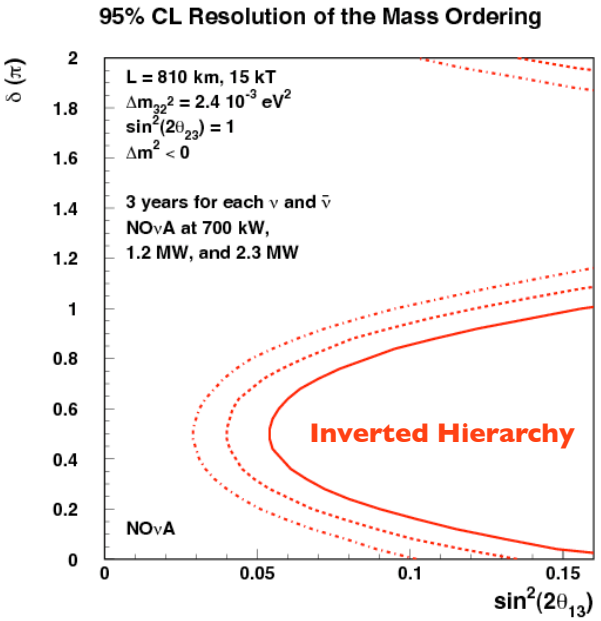
NOvA Physics

Expected sensitivity to $\sin^2(2\theta_{13})$ and mass hierarchy

- L = 810 km
- 14kT far detector
- $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV^2
- 3 years running neutrino and anti-neutrino beam configurations
- 700 kW (solid) 1,200 kW (dotted) 2,300 kW (dot-dash) beam power







Project Status

Beam:

- Horn1 and target design complete
- Kicker for Booster-Recycler in use
- First recycler injector magnet installed
- Accelerator shutdown: March 2012

Far Detector:

- Start construction: Jan 2012
- 1 block ready by start of shutdown
- 50% detector by end of shutdown
- Complete by early 2014

Near Detector:

- Cavern excavation during shutdown
- Prototype in operation at FNAL on the surface

Near Detector on Surface

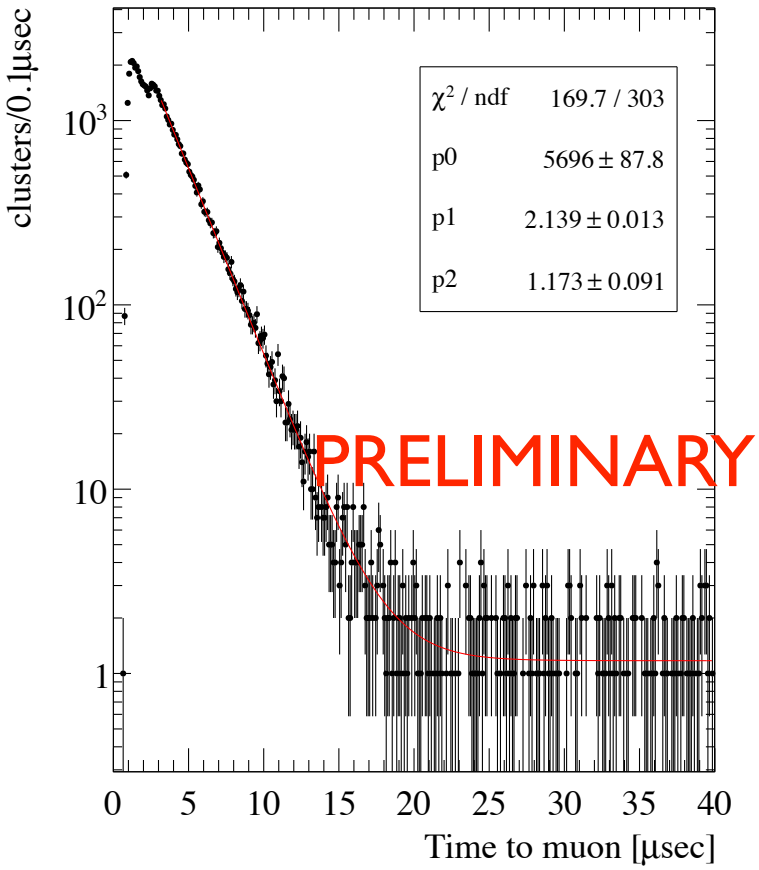
At the intersection of the NuMI and Booster beams

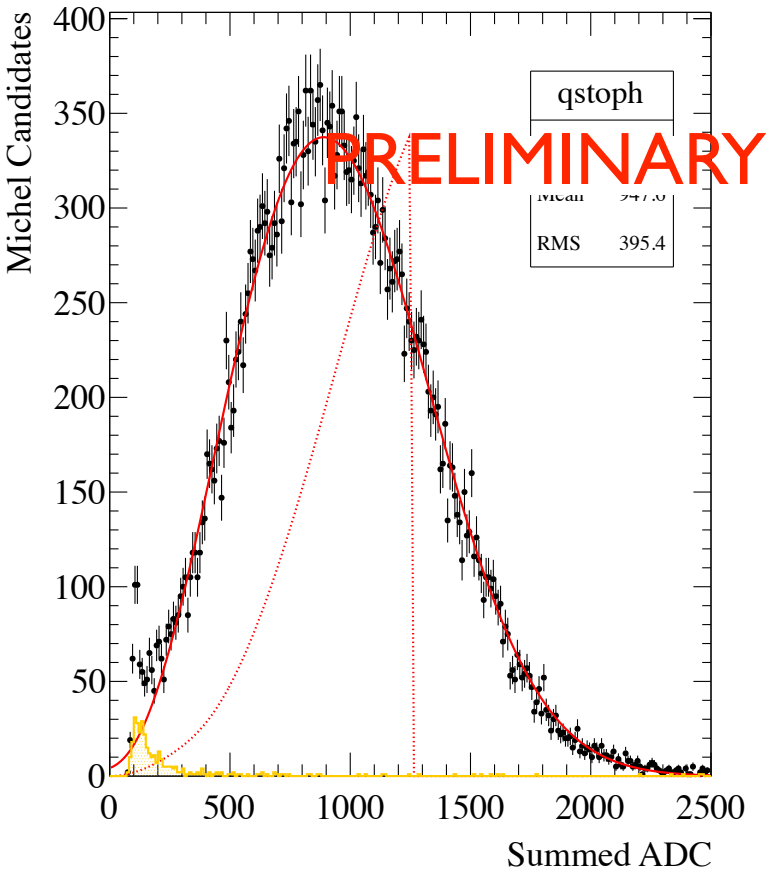
Run Goals:

- Test detector design and installation procedures
- Exercise calibration scheme
- Benchmark MC
- Demonstrate electron neutrino selection, background suppression
- Verify cosmic background suppression
- Study nuclear hadronization models
- Quasi-elastic cross section at 2 GeV
- Constrain neutrino flux
- Booster short-baseline oscillations

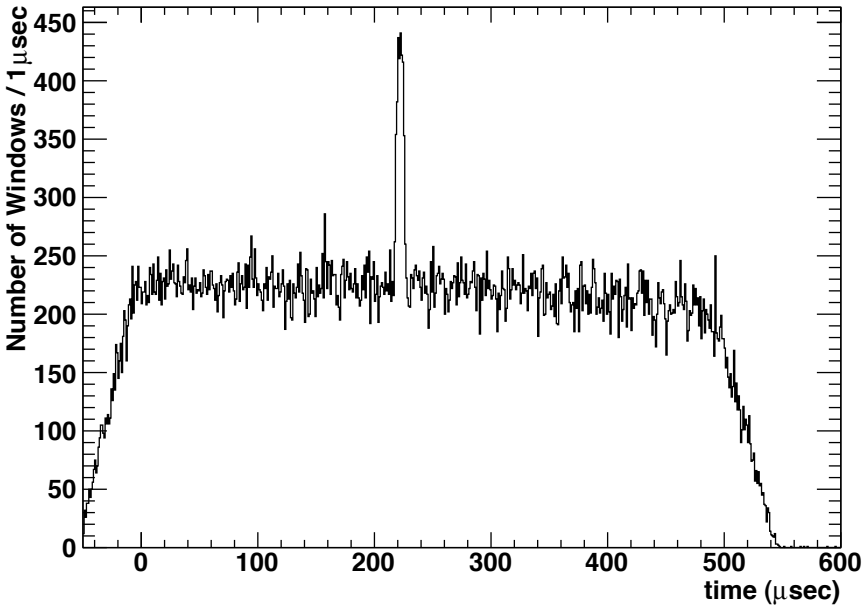
Michel Electrons (Data)

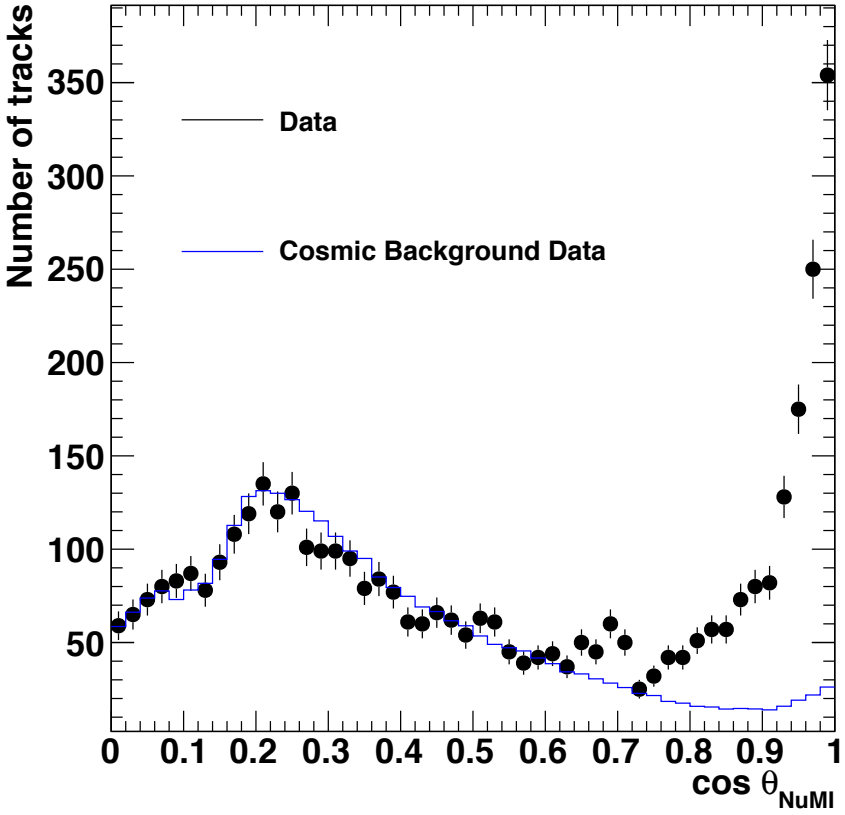
Use Michel electrons for electro-magnetic energy calibration





Finding NuMI Neutrinos



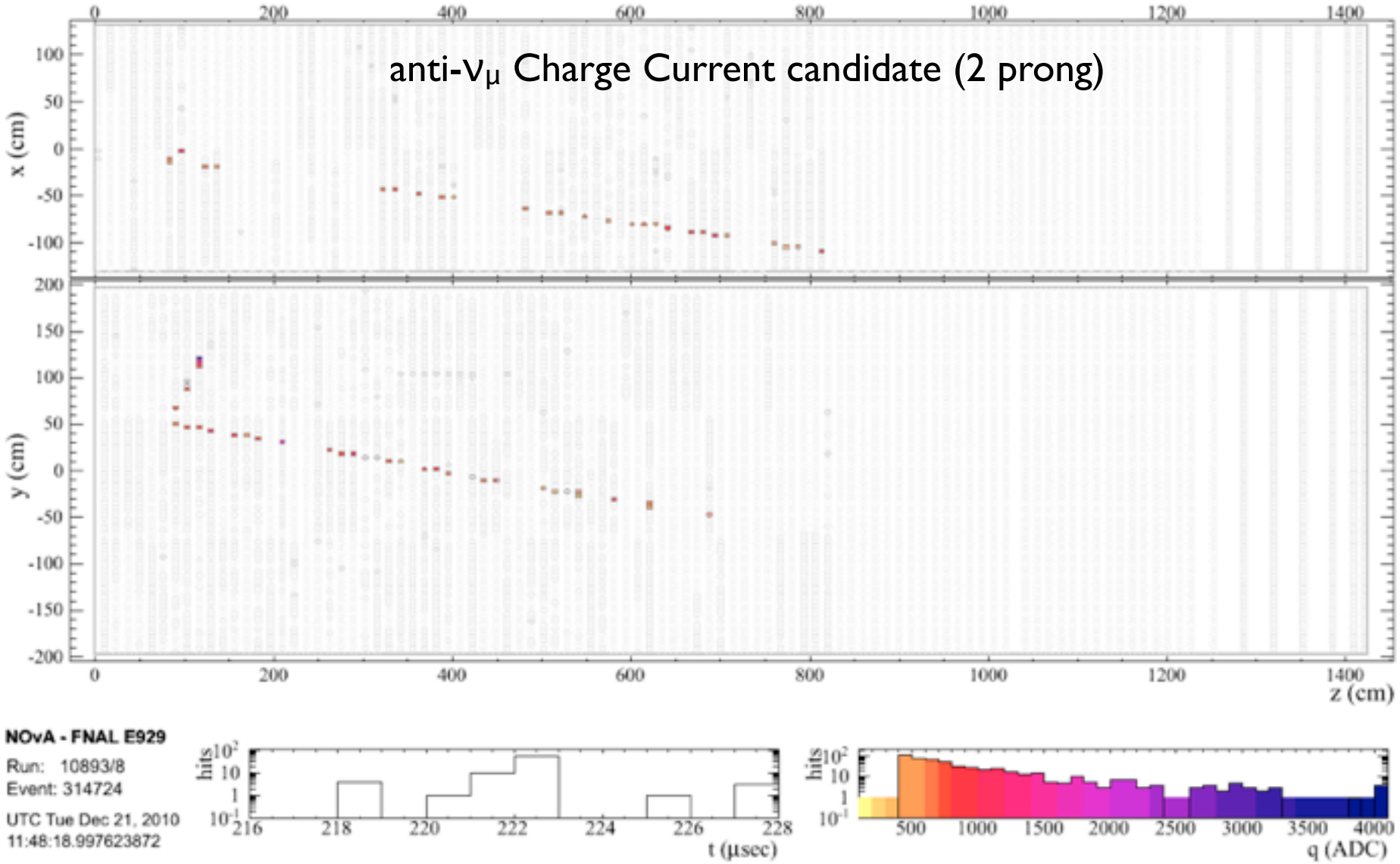


110 mrad off NuMI axis

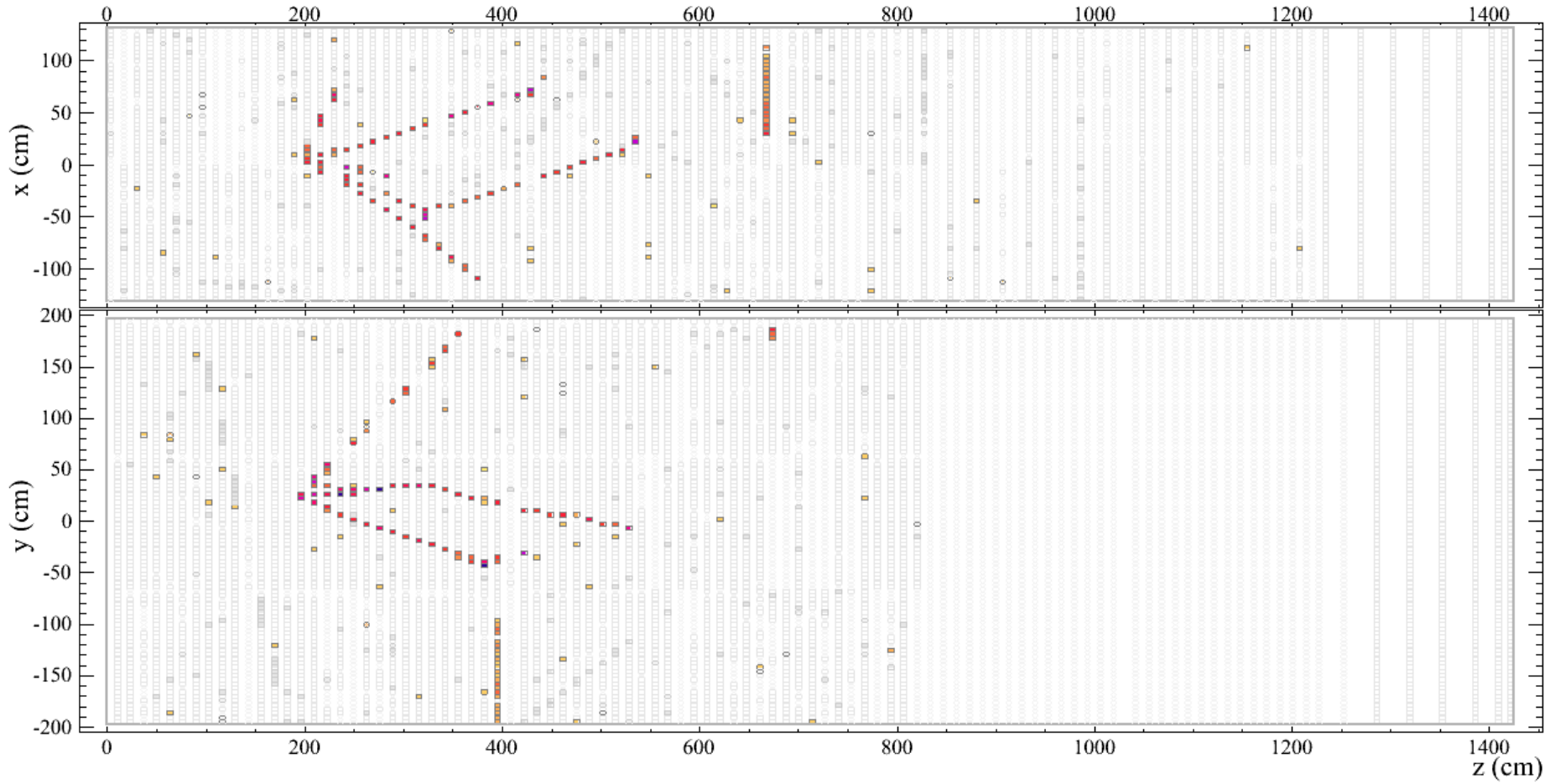
5.6×10^{19} POT "anti-neutrino" beam, 1001 NuMI events (69 cosmic BG)

8.4×10^{18} POT "neutrino" beam, 253 NuMI events (39 cosmic BG)

NuMI Anti-neutrino Event



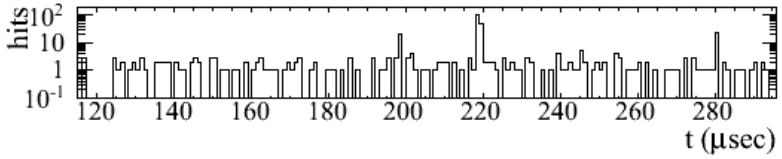
NuMI Event

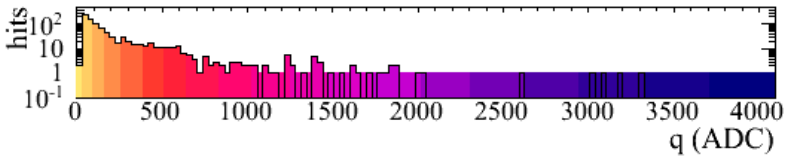


NOvA - FNAL E929

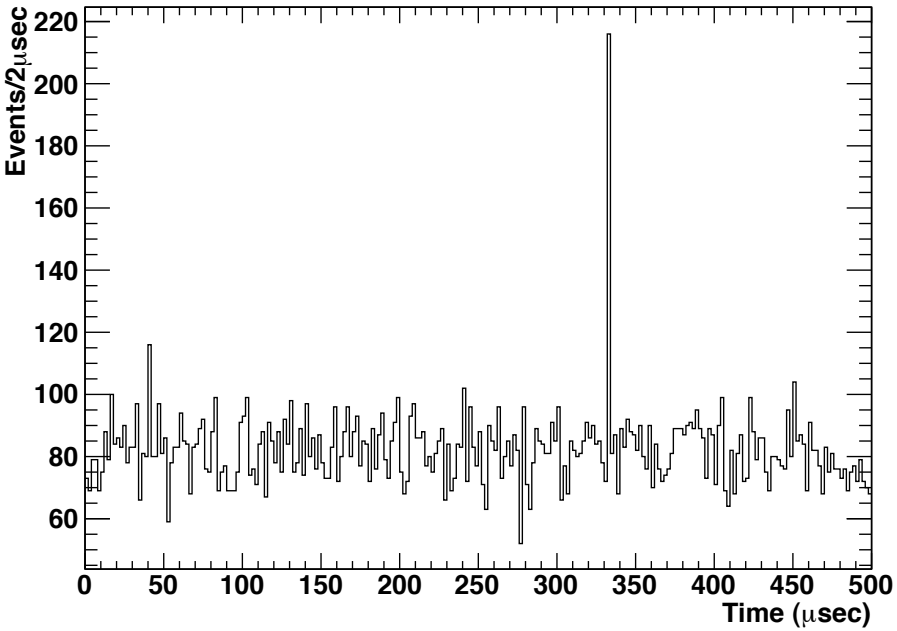
Run: 11945/20
Event: 1043748

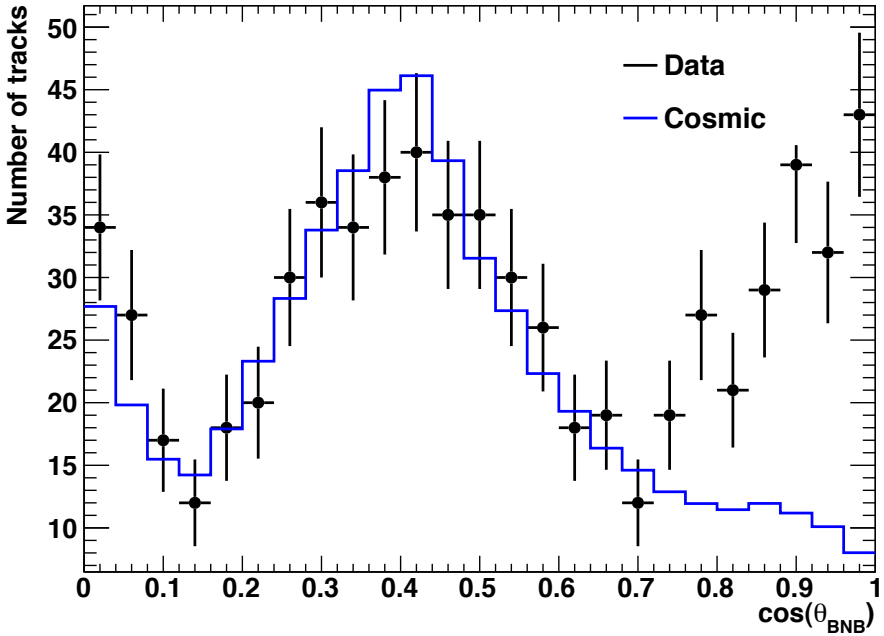
UTC Sat Apr 9, 2011
19:08:36.717589440





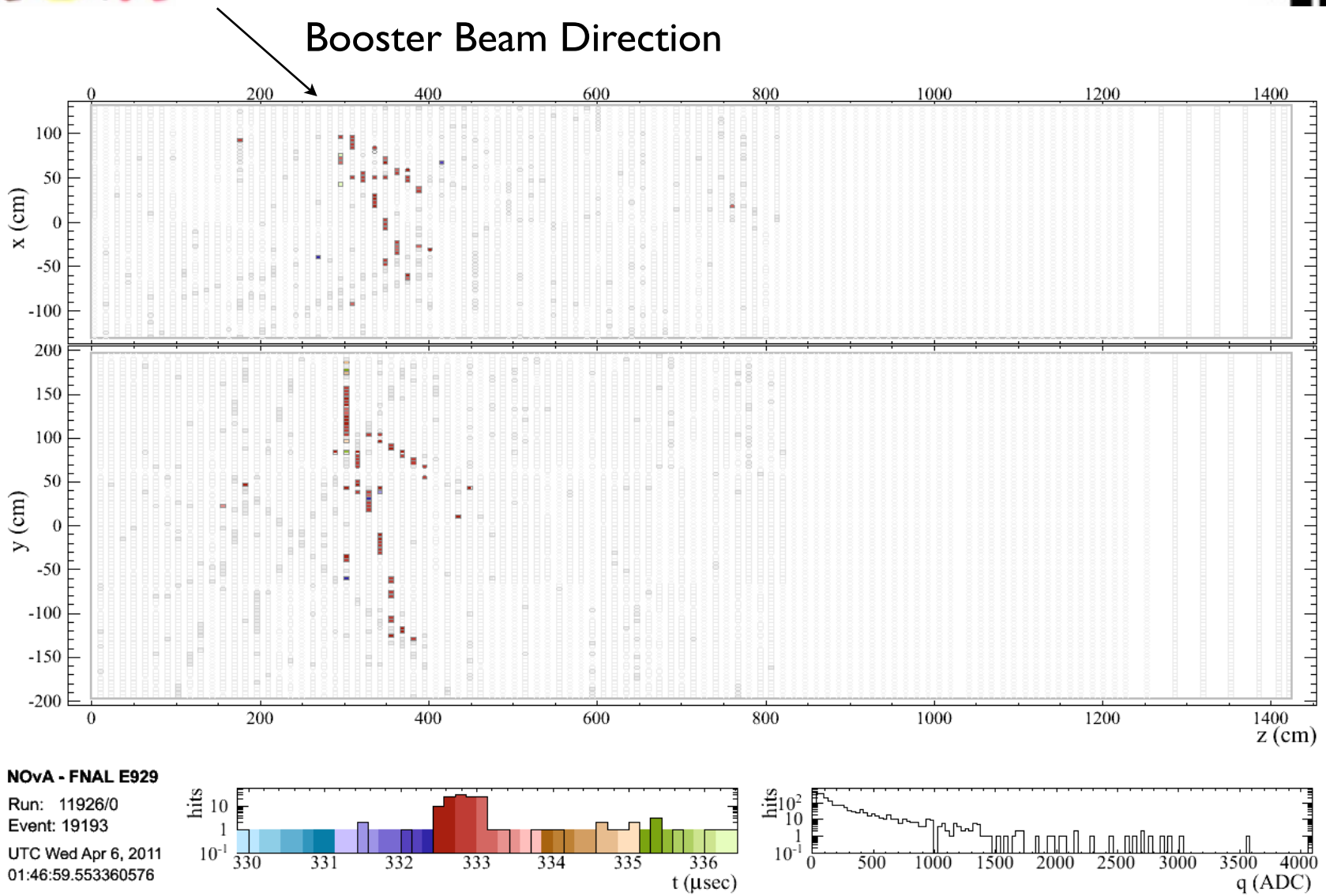
Finding Booster Anti-Neutrinos



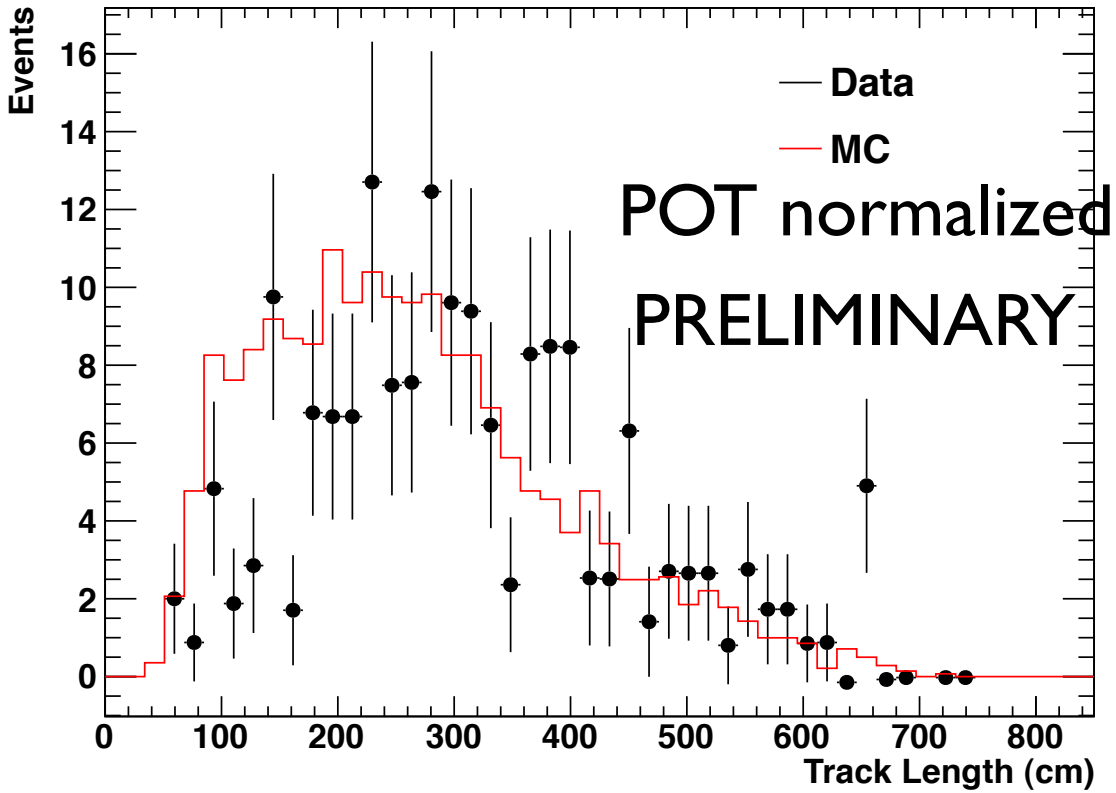


Detector is on the Booster neutrino beam axis
Detector axis rotated ~20° relative to the beam axis
3×10^{19} POT reverse horn current beam, 222 booster events (92 cosmic BG)

Booster Anti-neutrino Event



Comparisons to MC



Early look at contained events indicates NuMI MC event rate agrees with data

Summary

NOvA is on track to make many important contributions to neutrino physics

- Measurement of θ_{13}
- Determination of mass hierarchy
- More precise measurements of Δm_{32}^2, $\sin^2(2\theta_{23})$

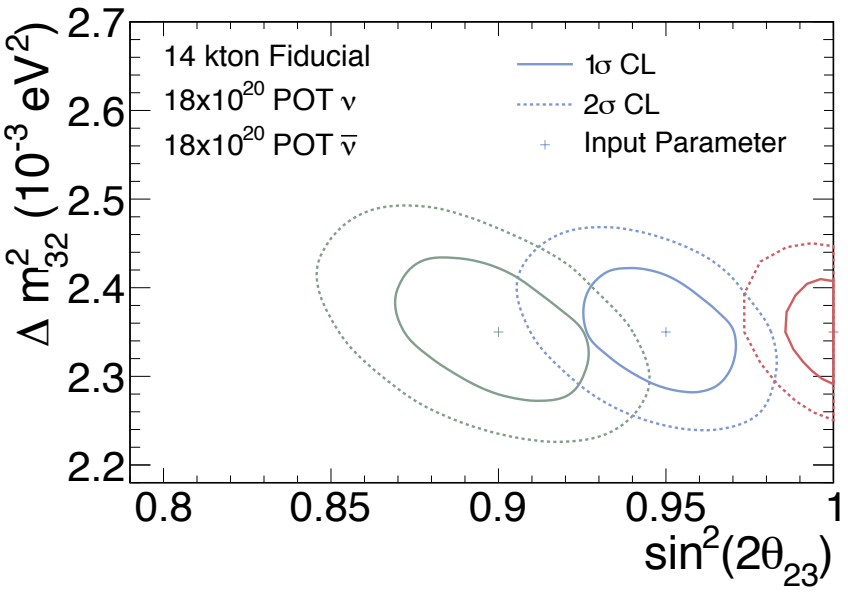
Far detector construction coming soon

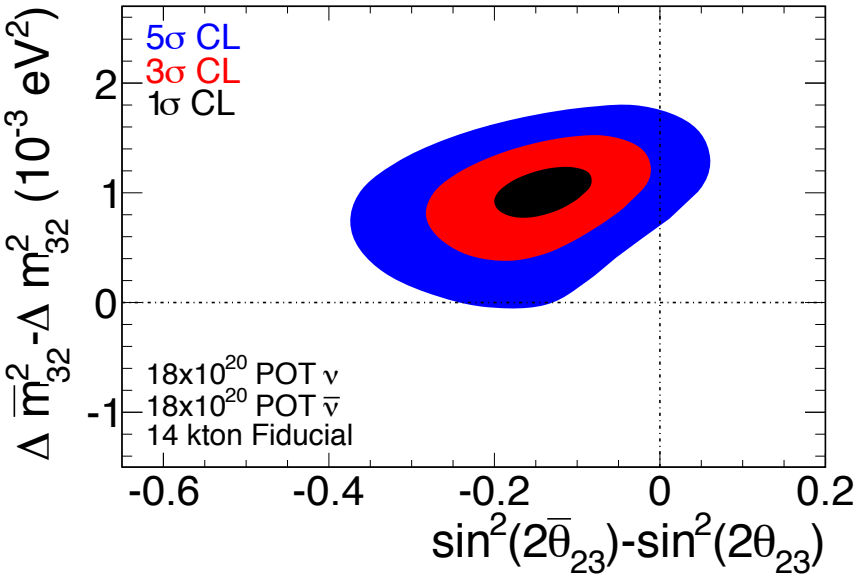
Near detector on the surface taking neutrino data now!

Challenge: Fill this Hall

Back Up Slides

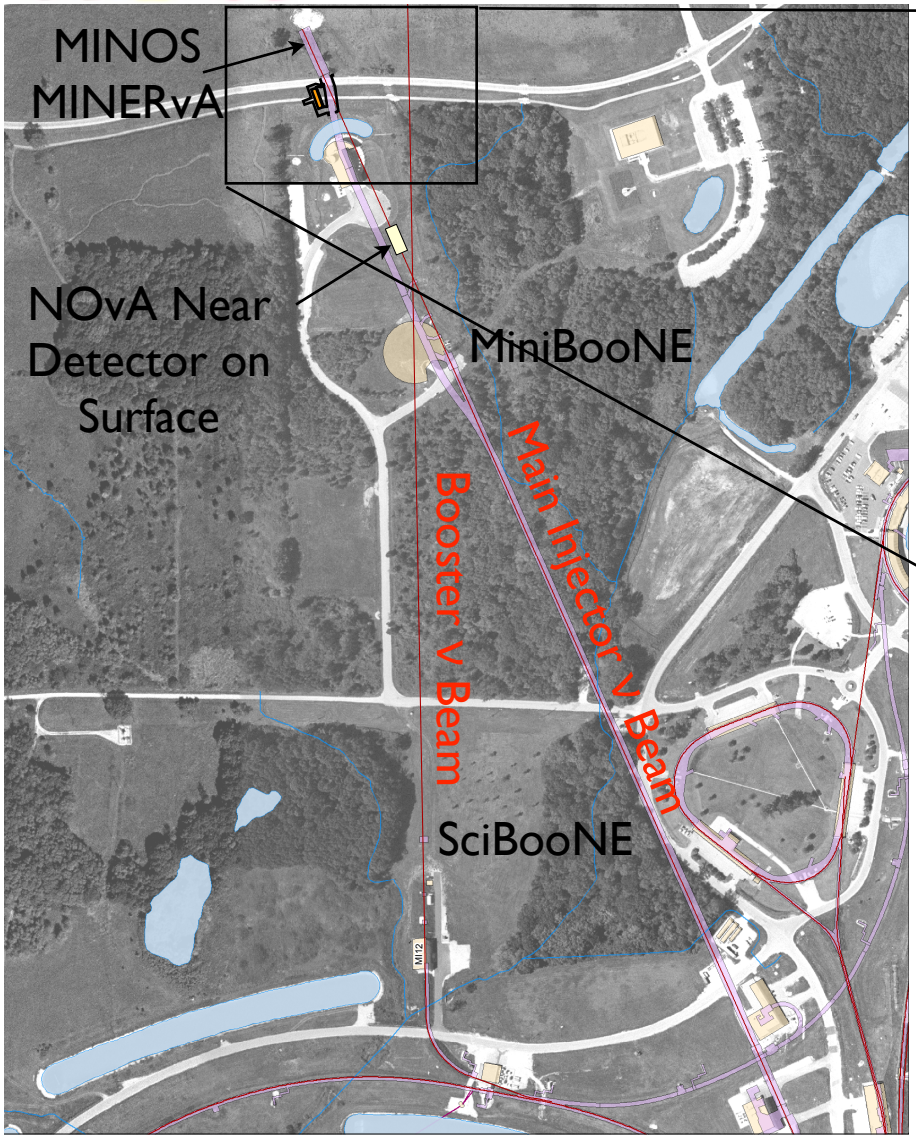
Muon Neutrino Disappearance

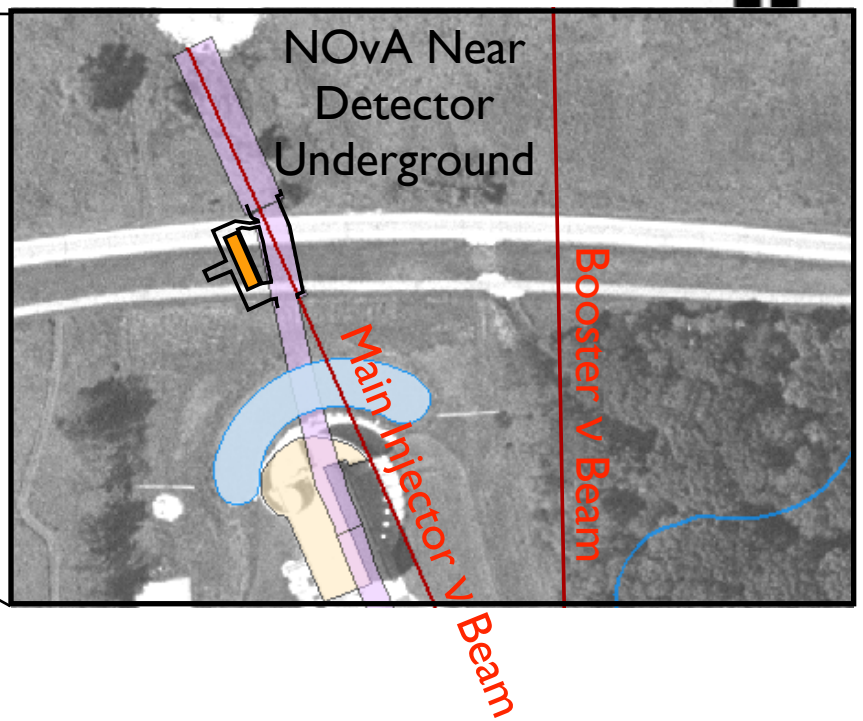




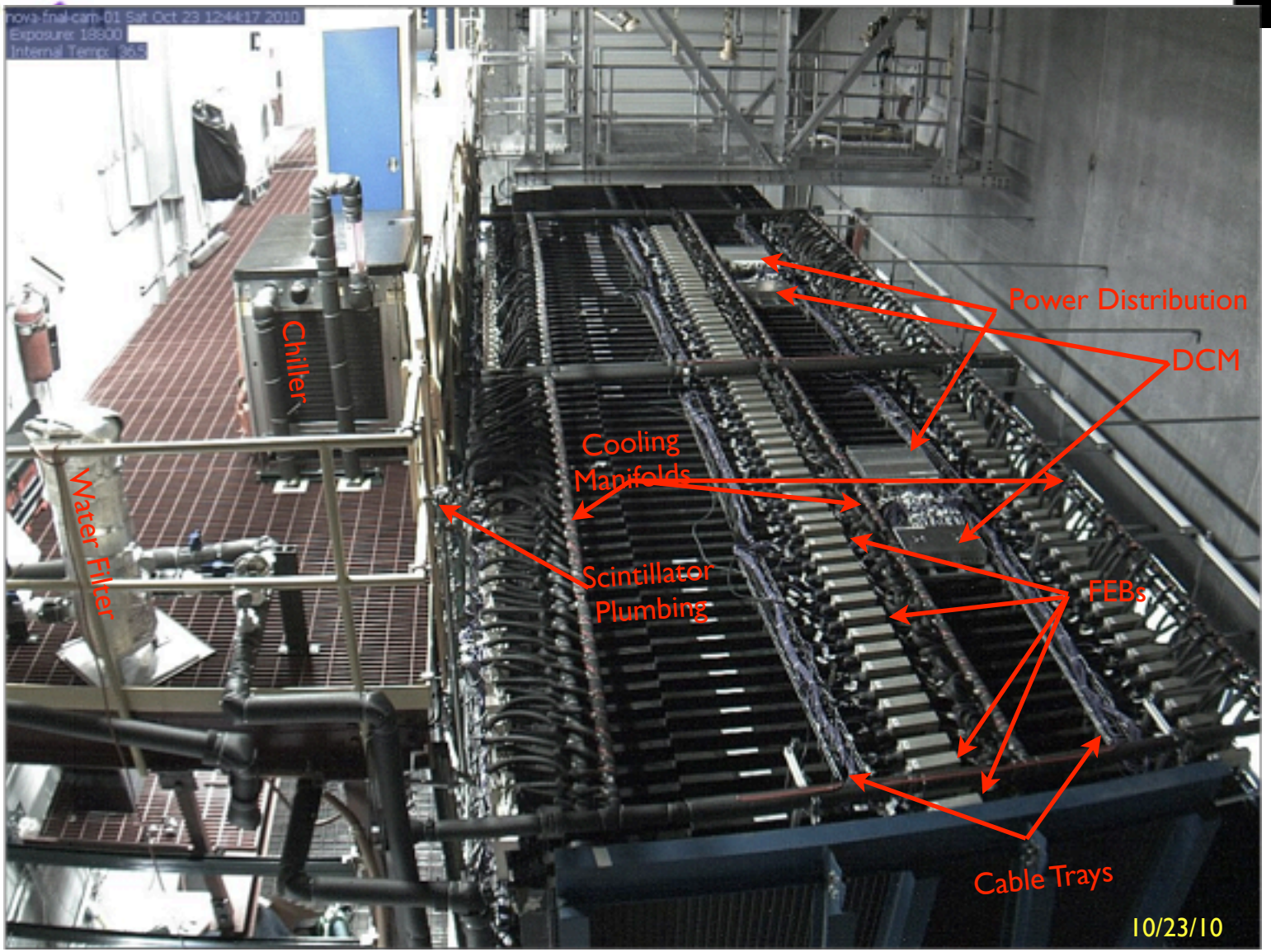
Sensitivity to (Δm^2, $\sin^2(2\theta_{23})$) after 3 years each of neutrino beam and antineutrino beam

Near Detector



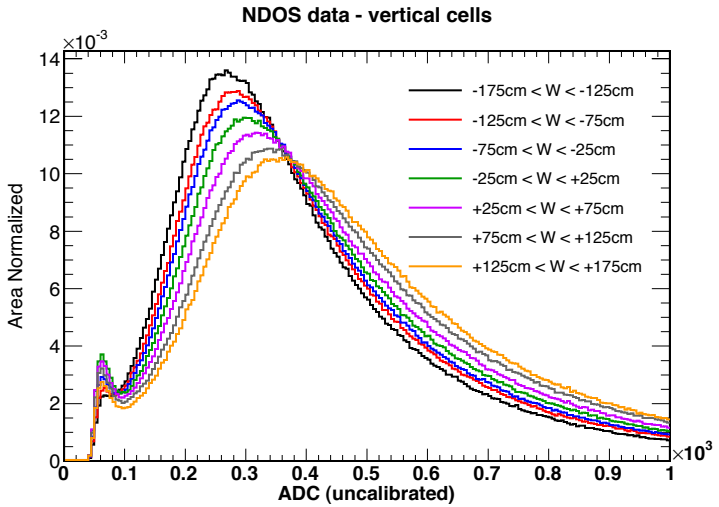


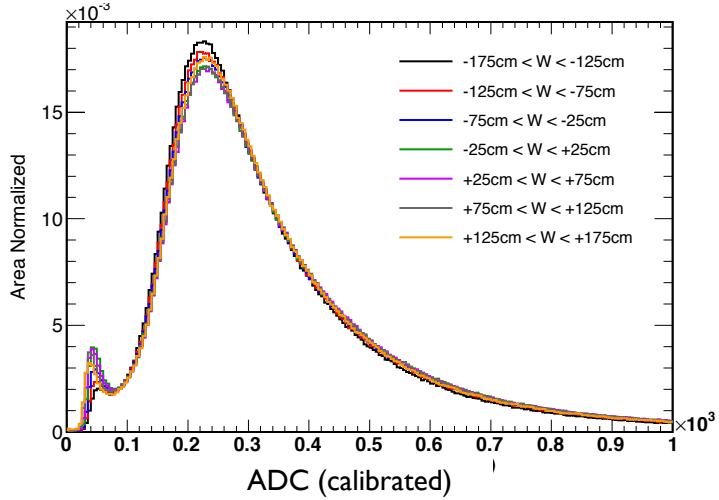
Near Detector Status: (Top)

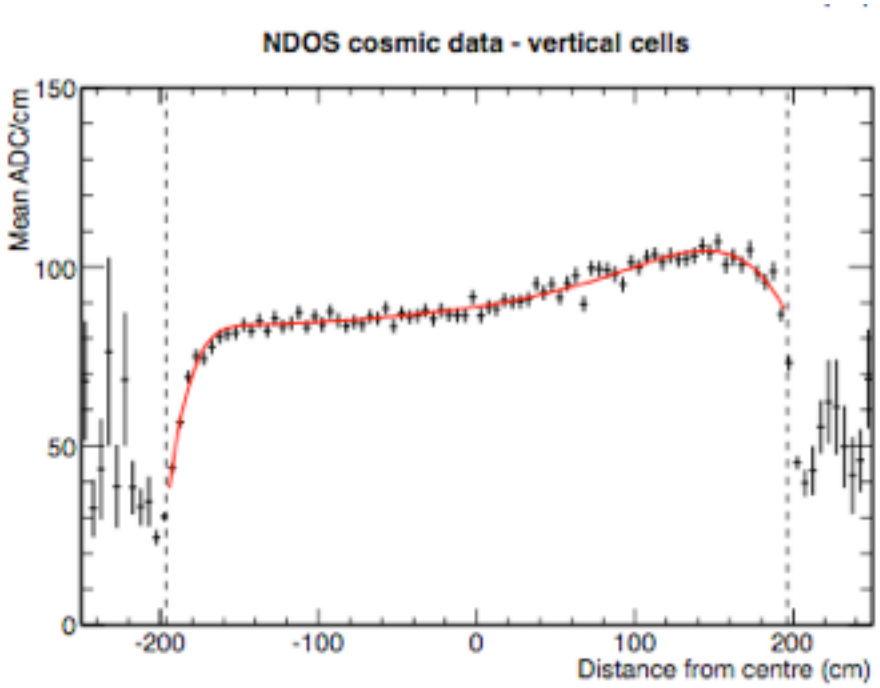


Calibration

Cosmic muons provide intra-detector calibration source







Accelerator and NuMI Upgrades (ANU)

Recycler Ring (RR)

- New injection line into RR
- New extraction line from RR
- New 53MHz RF system
- Instrumentation upgrades

Main Injector

- Two 53MHz RF cavities
- Quad power supply upgrade
- Low Level RF System

NuMI

- Change to medium energy ν beam configuration (target & horn configuration)
- Cooling & power supply upgrades