THE NOvA EXPERIMENT

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College of William and Mary

Neutrinos Have Mass!

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

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

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation
- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
  - The mixing amplitudes ($U_{\alpha i}$)

The PMNS Mixing Matrix

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

- (12) Sector: Reactor + Solar, L/E~15,000 km/GeV

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

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \qquad ^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \text{C.L.})$$

- (13) Sector mixing not yet observed

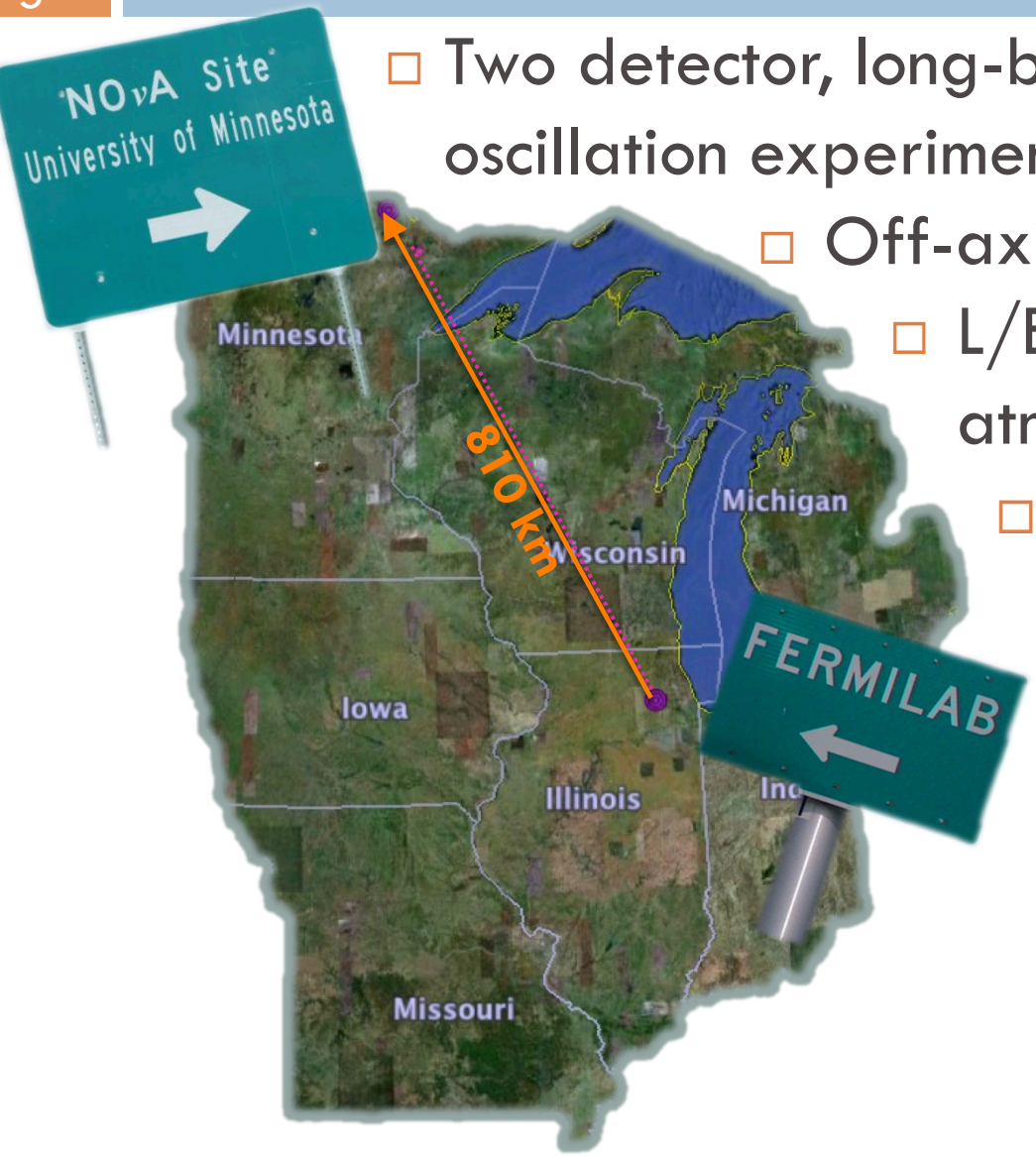
$$^{**}\sin^2(2\theta_{13}) < 0.15 - 0.16$$

†PRD 83.052002(2011)
††PRL 106. 181801(2011)
*SuperK Preliminary, Nu2010
** Eur.Phys. C27:331-374,2003

Why measure all these angles?

- Precision measurements provide a 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?
  - Is it big enough to account for matter vs. antimatter asymmetry in the Universe?
- Small neutrino mass suggests a heavy partner (see-saw mechanism)— Neutrinos provide a window to physics at the GUT scale!

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 (with both neutrinos and antineutrinos)
        - measure/limit θ_{13}
        - determine mass hierarchy
        - constrain CP violating phase
        - precision measurements of Δm^2, θ_{23}

ν_e Appearance

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

"Atmospheric" Term
Depends on Δm^2 and unknown θ_{13}

"Solar" Term
<1% for current accelerator experiments

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

Interference Term

- for neutrinos

+ for antineutrinos

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

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

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

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

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

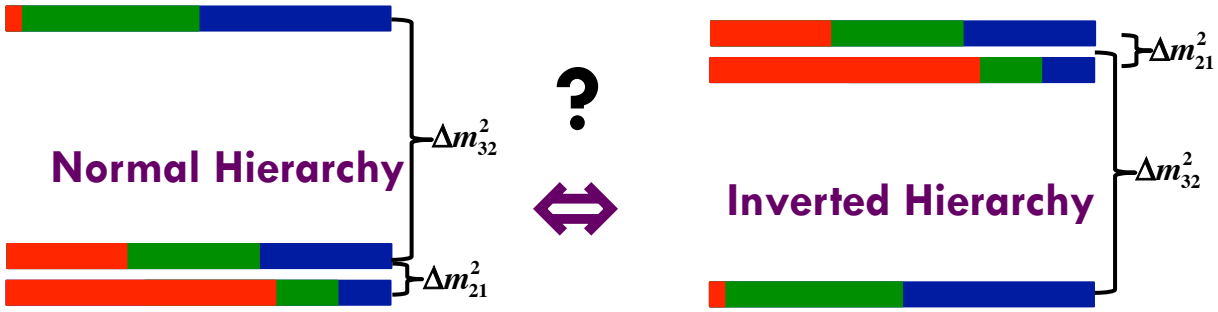
In matter, additional term in Hamiltonian from ν_e + e CC scattering modifies oscillation probability, ~30% effect in NOvA

ν_e Appearance

- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \left| \sqrt{P_{atm}}\, e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

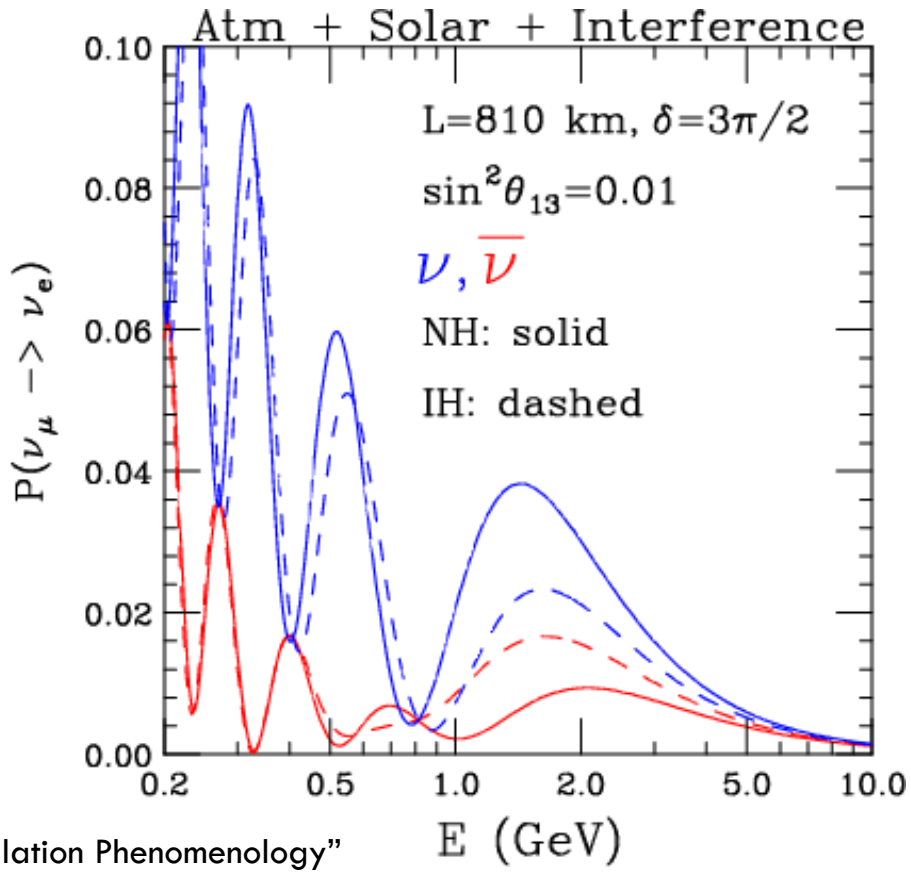
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - aL\right) \left(\frac{\frac{\Delta m^2_{31} L}{4E}}{\left(\frac{\Delta m^2_{31} L}{4E} - aL\right)} \right)^2 \qquad P_{sol} \approx \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(aL) \left(\frac{\frac{\Delta m^2_{21} L}{4E}}{aL} \right)^2$$



Oscillation probability depends on sign of Δm^2

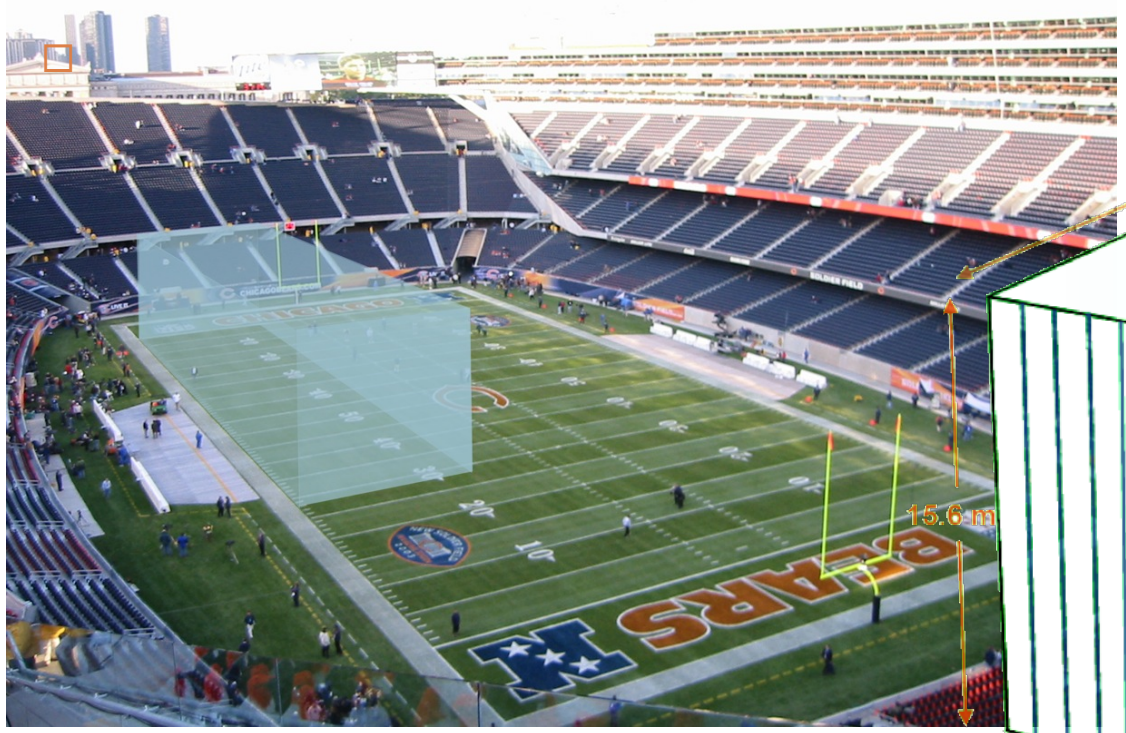
ν_e Appearance

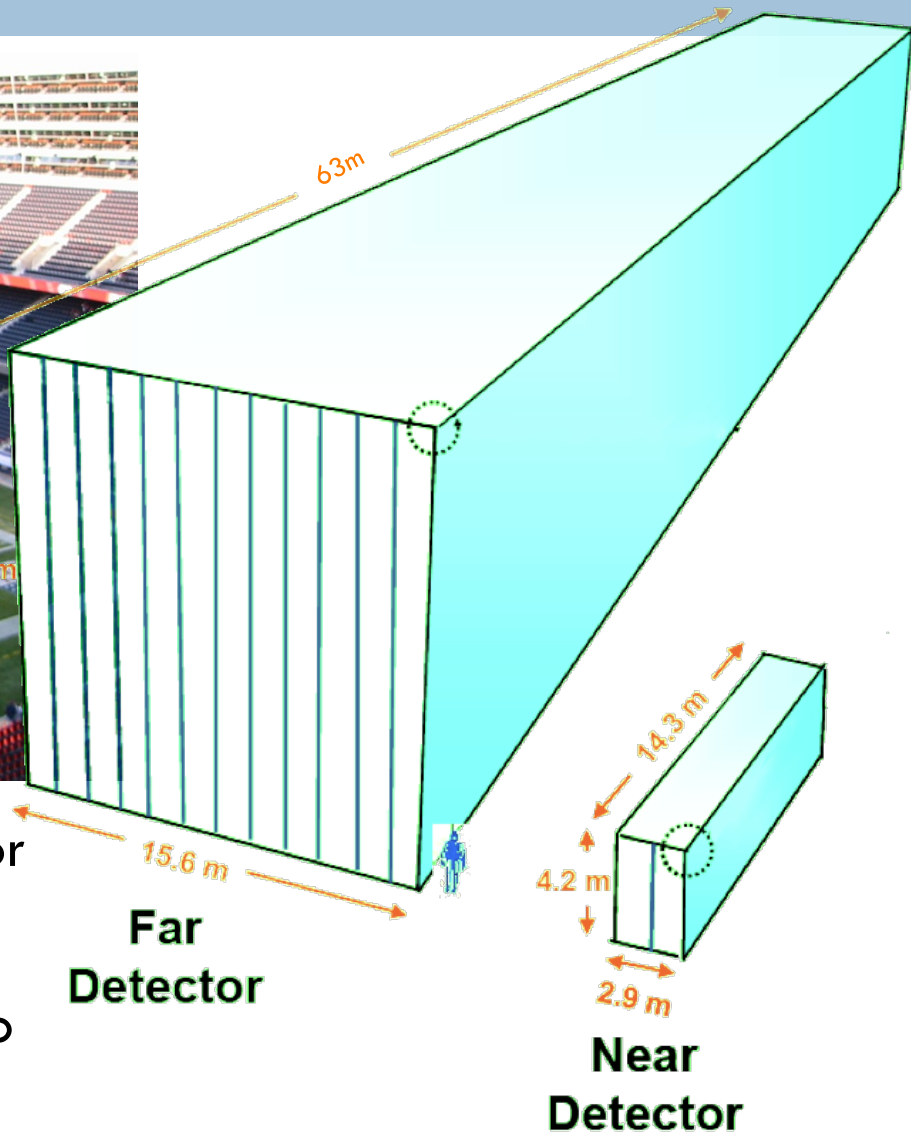
- At L/E~500 km/GeV, dominant oscillation mode is $\nu_\mu \rightarrow \nu_\tau$
- A few percent of the missing ν_μ could change into ν_e



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

The NOvA Detectors





- Massive, Low-Z, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector to mitigate systematic uncertainties
  - 220 ton Near Detector, 1 km from source

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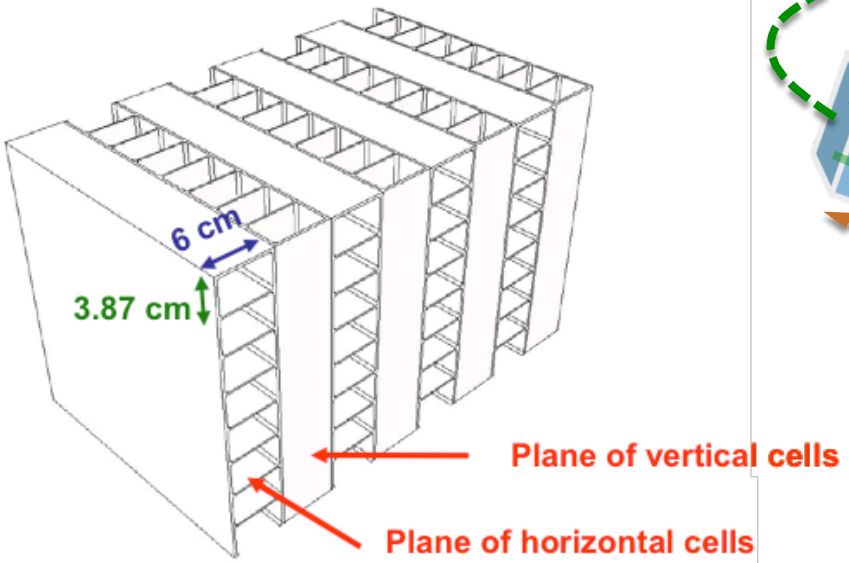
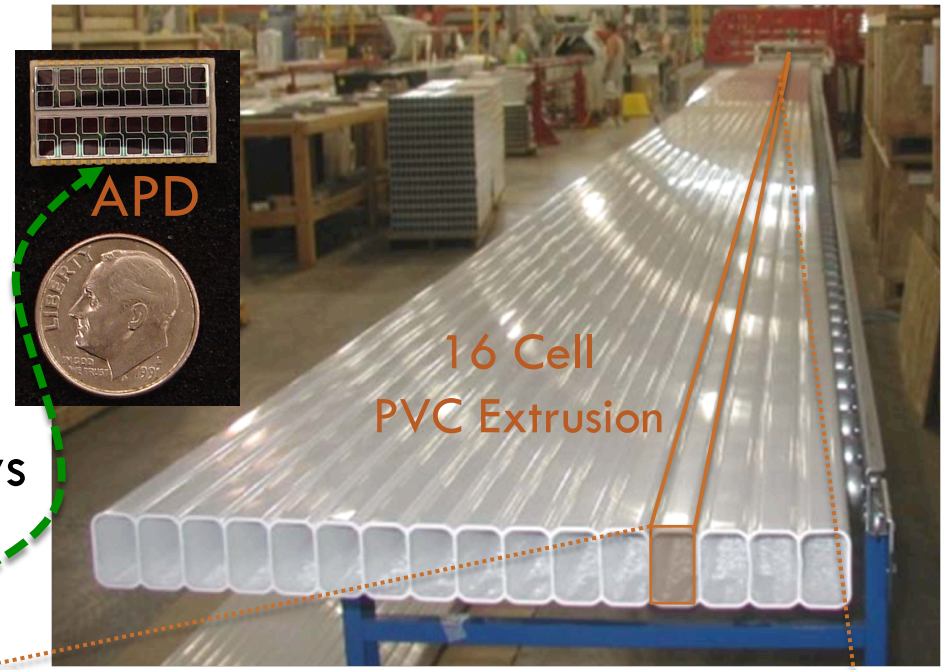
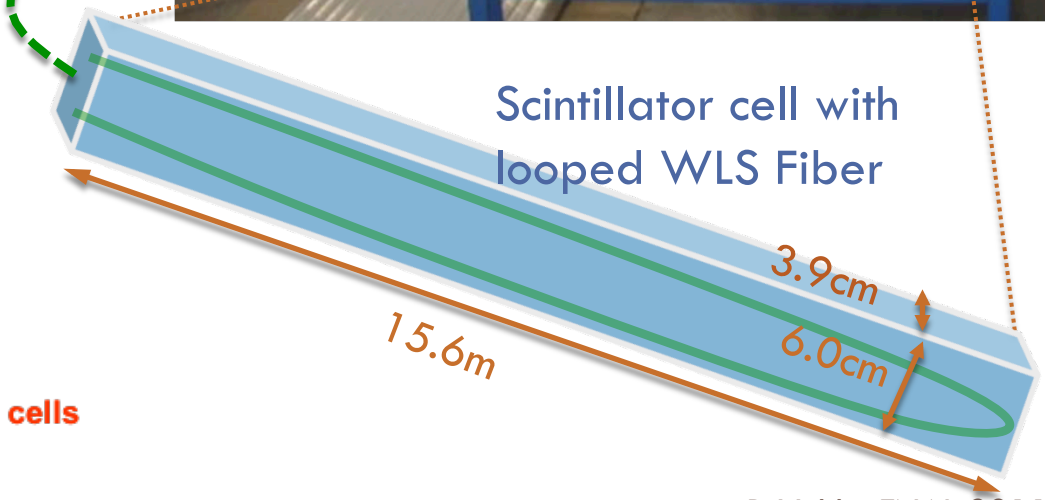
Detector Technology

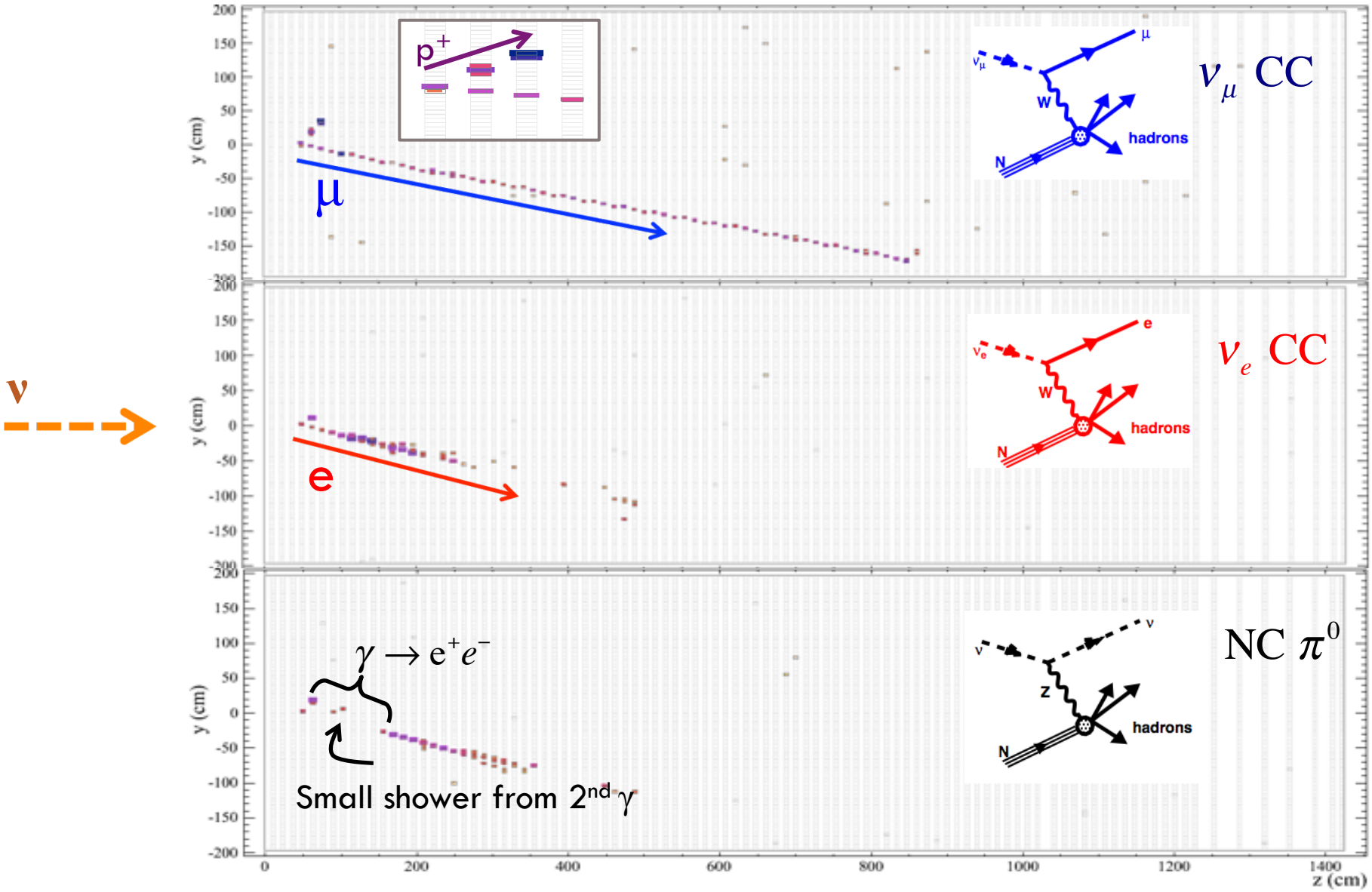
- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - muon crossing far end=38 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer



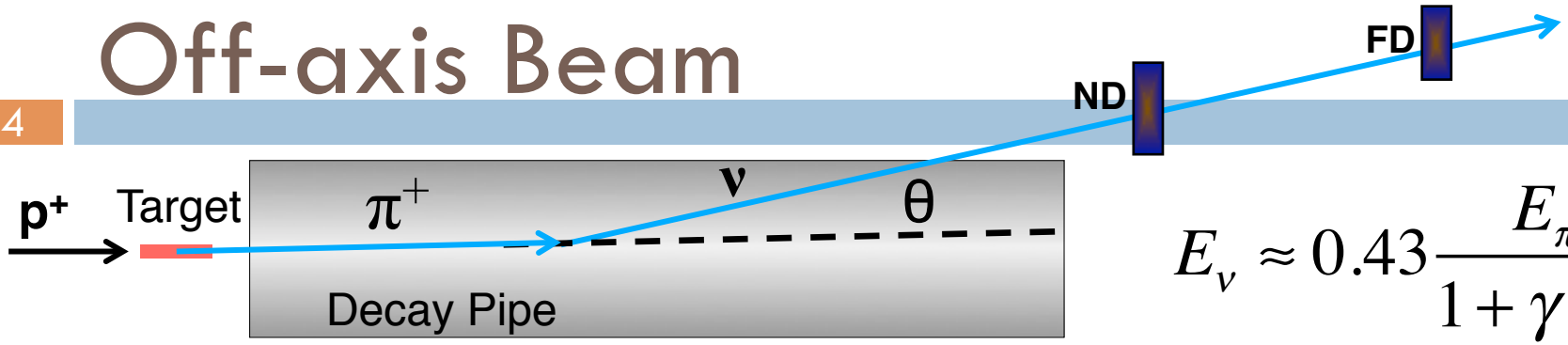




MC Events in NOvA

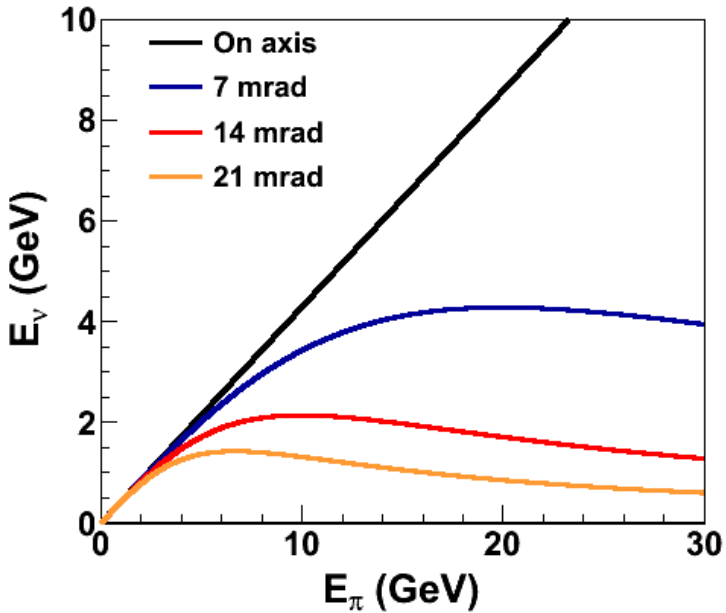


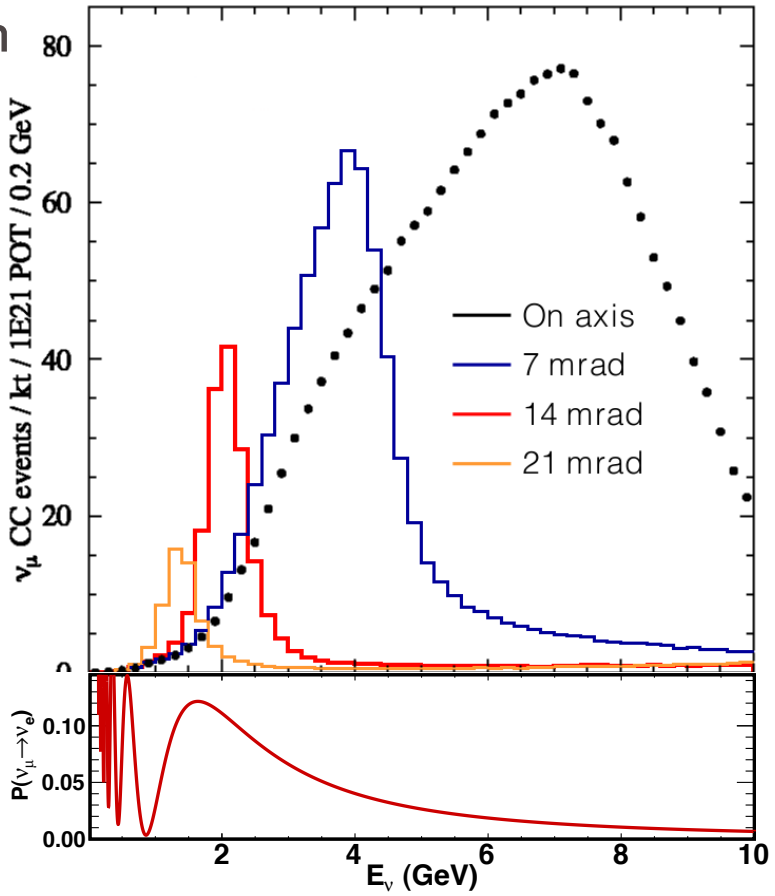
Off-axis Beam



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

- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events





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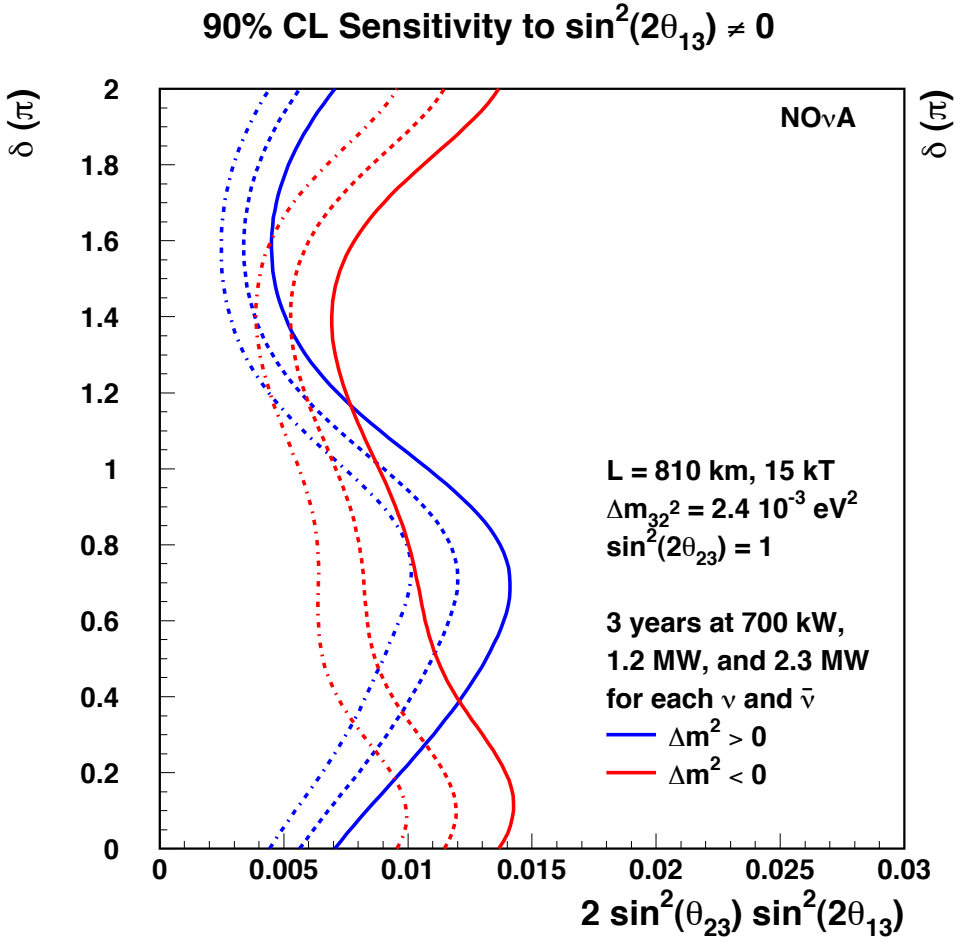
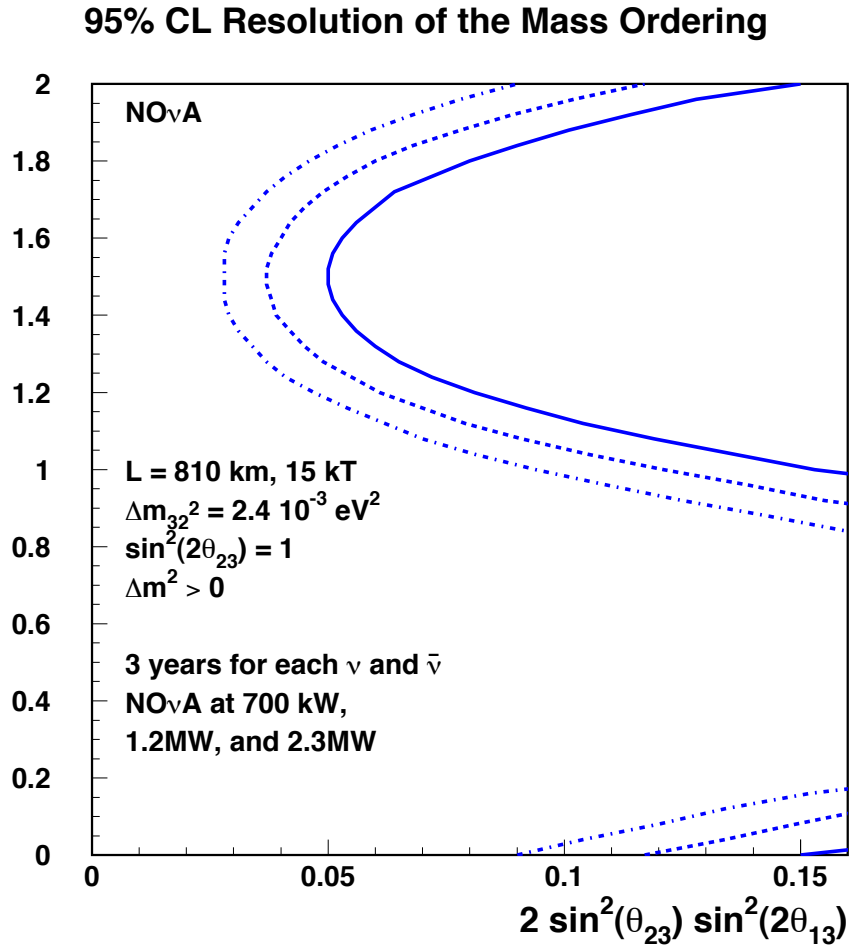
Sensitivity





- Sensitivity to $\sin^2(2\theta_{13})$ after 3 years each of neutrino beam and antineutrino beam
- Sensitivity to mass hierarchy

Project Timeline

- Beam:
  - Accelerator shutdown to install upgrades for 700kW beam: March 2012
  - Horn1 and target design complete
  - Kicker for Booster-Recycler in use
  - First recycler injector magnet installed
- FD:
  - Start construction: Jan 2012
  - 1 block ready by start of shutdown
  - 50% detector by end of shutdown
  - Complete by early 2014
- ND:
  - Cavern excavation during shutdown
  - Prototype in operation at FNAL on the surface

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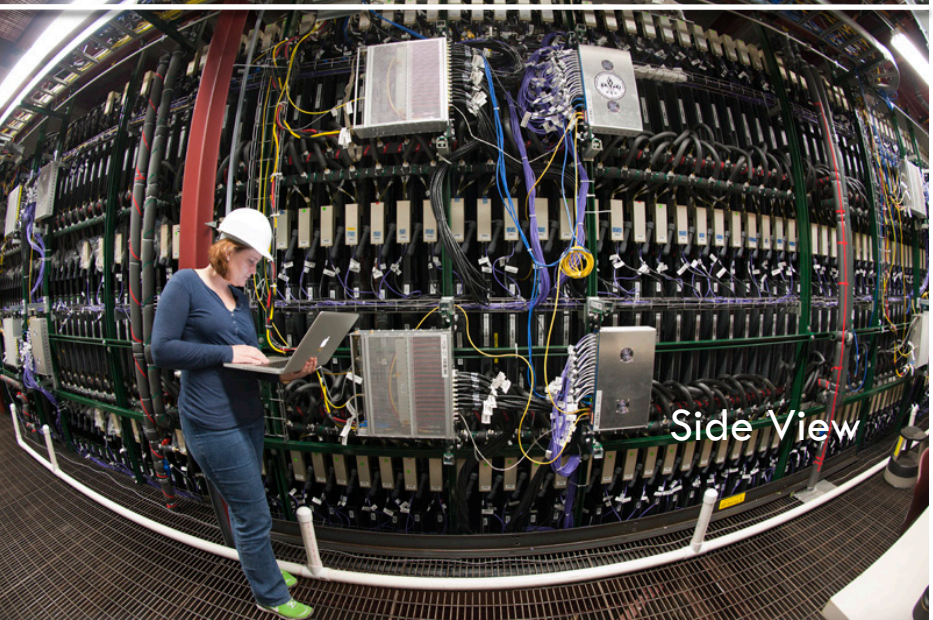
NDOS

- 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

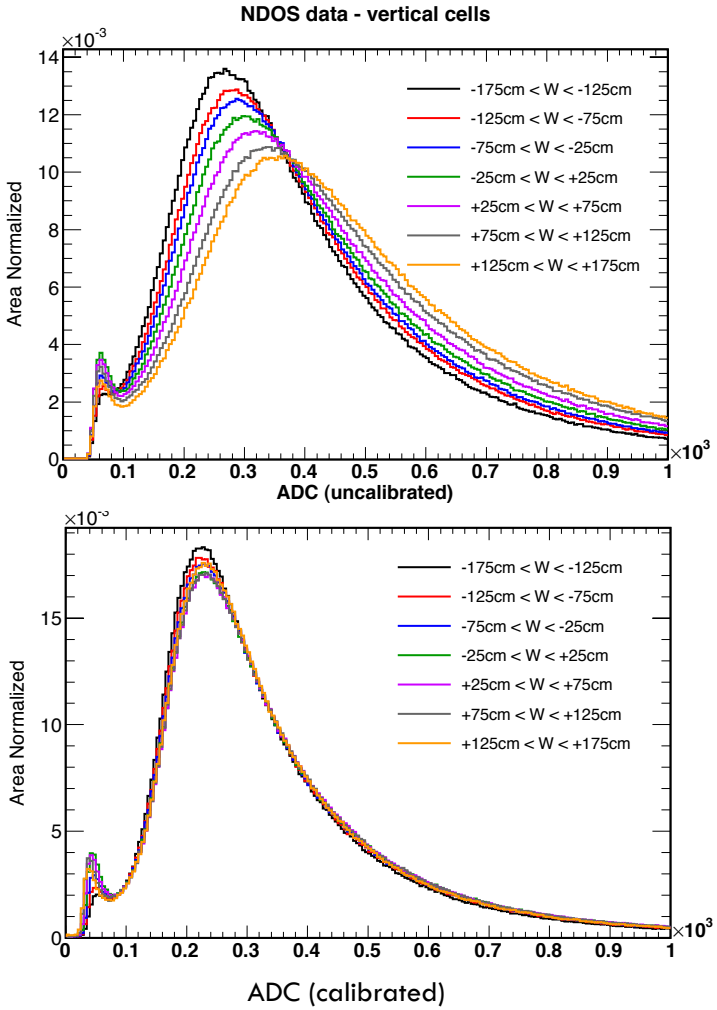
Lessons Learned

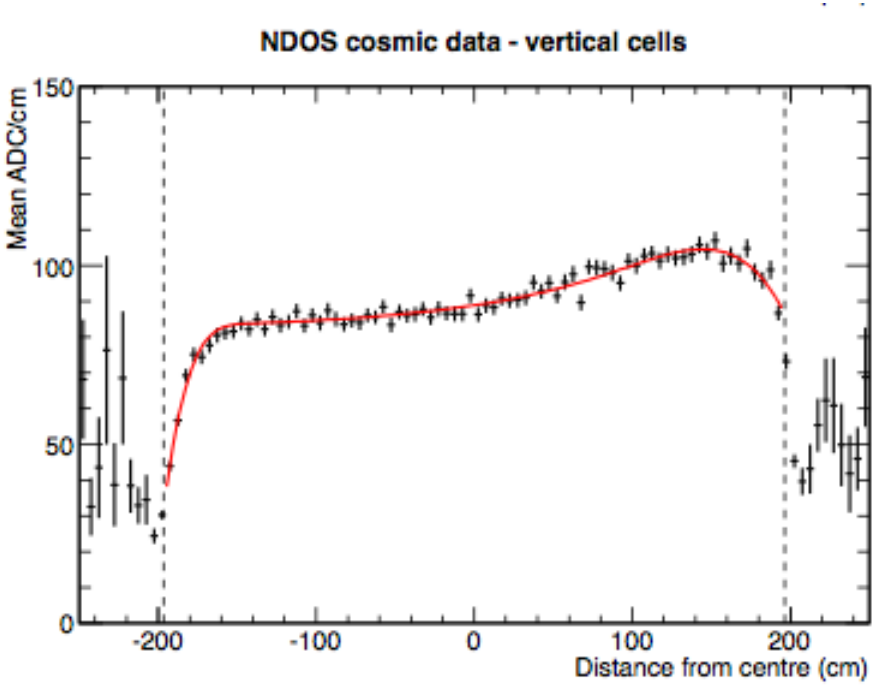


- 22% of module manifolds developed cracks during detector installation
  - "Splints" to fix NDOS
  - Changes to pressure testing
  - Redesign of manifolds
- APDs and oil do not mix
  - plan to coat APDs with epoxy
  - revamped procedures to ensure cleanliness is maintained during industrial scale installation

Calibration

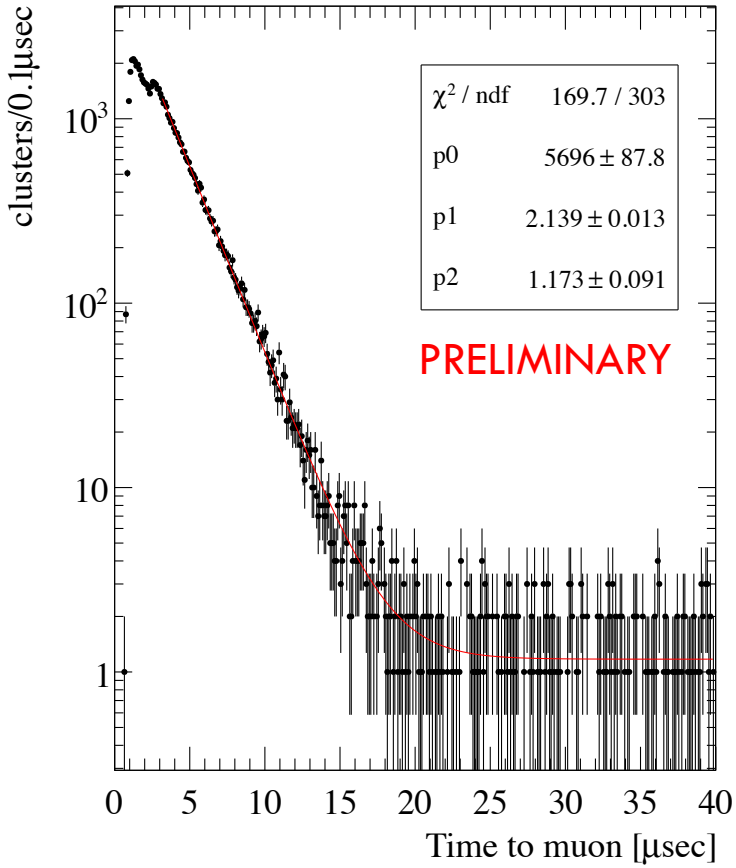
- Cosmic muons provide intra-detector calibration source

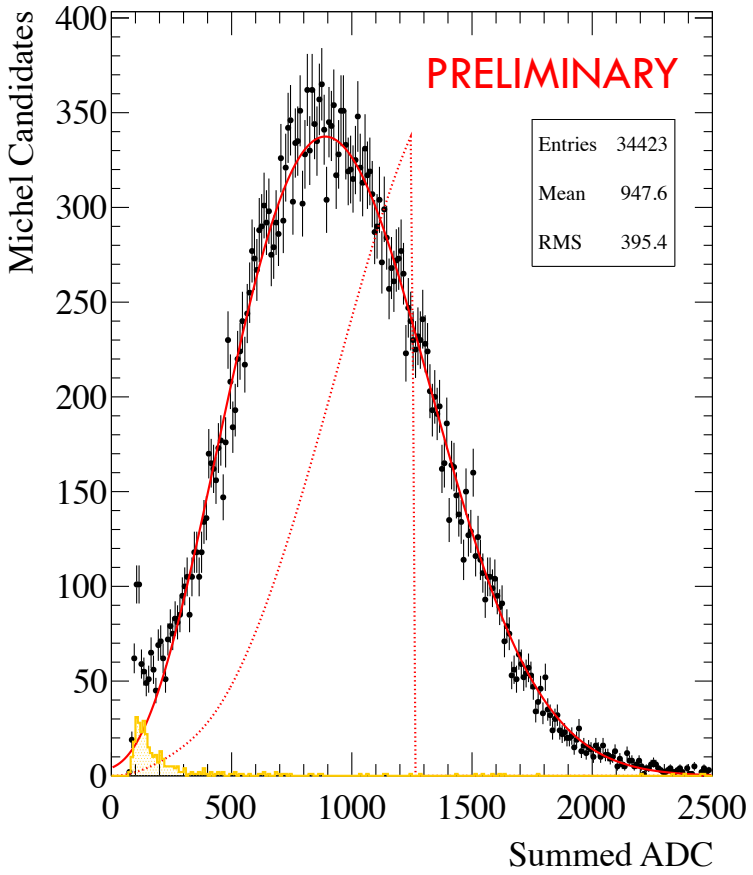




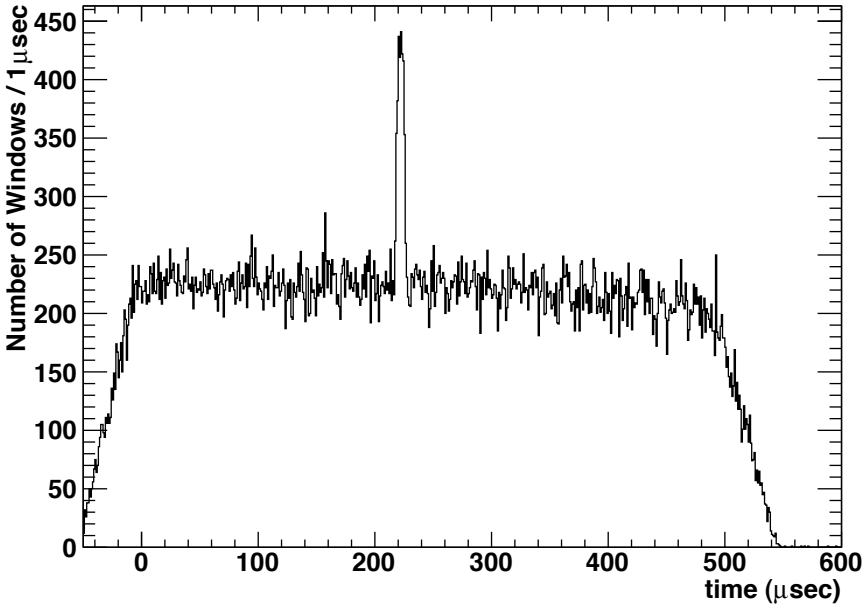
Michel Electrons

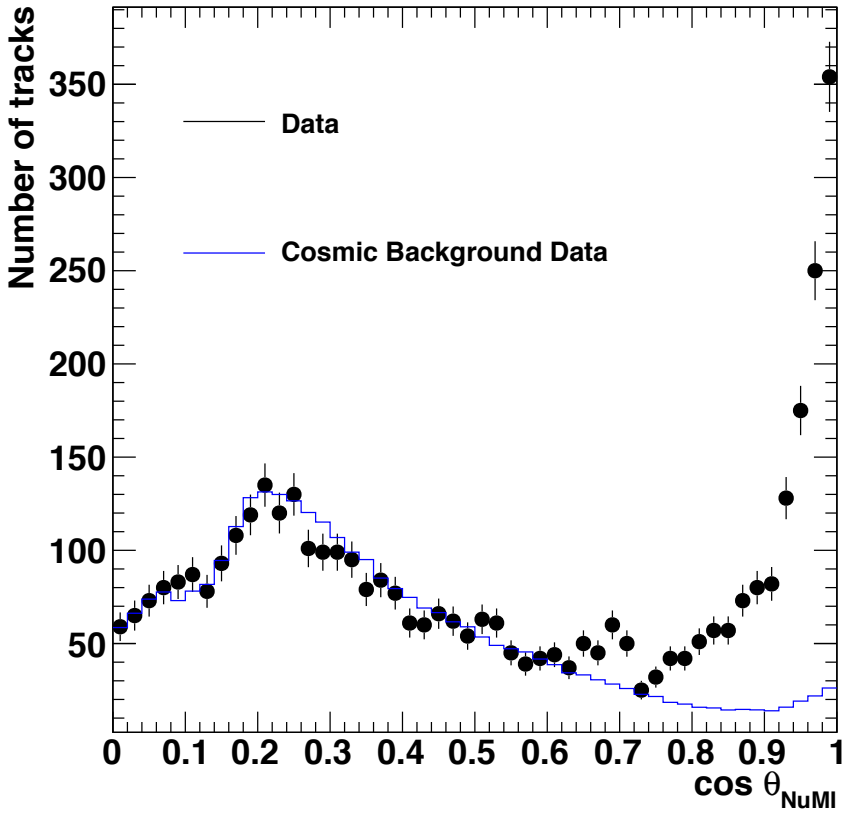
- Use Michel electrons for electro-magnetic energy calibration





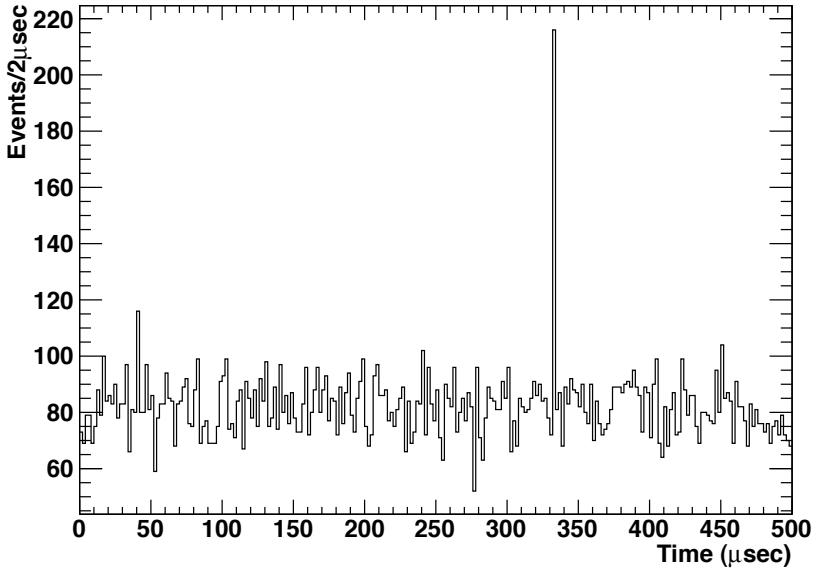
Finding NuMI Neutrinos

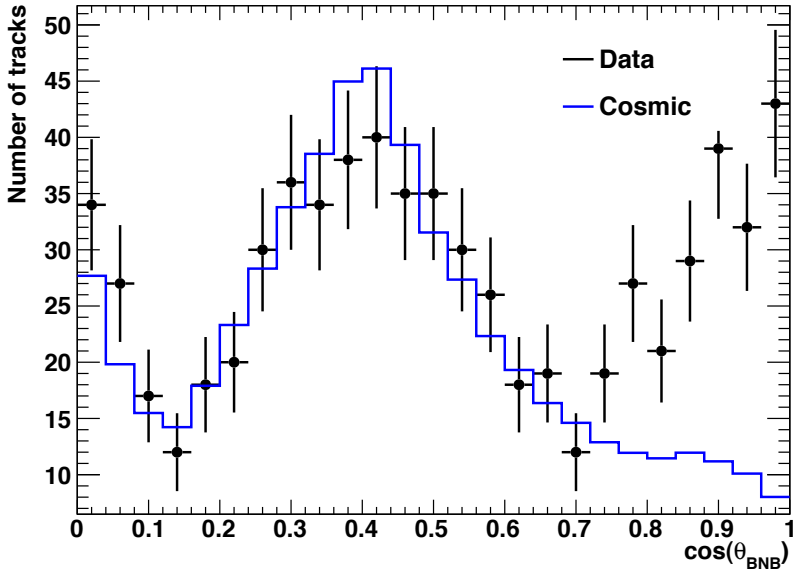




- 110 mrad off NuMI axis
- 5.6×10^{19} POT reverse horn current beam, 1001 NuMI events (69 cosmic BG)
- 8.4×10^{18} POT forward horn current beam, 253 NuMI events (39 cosmic BG)

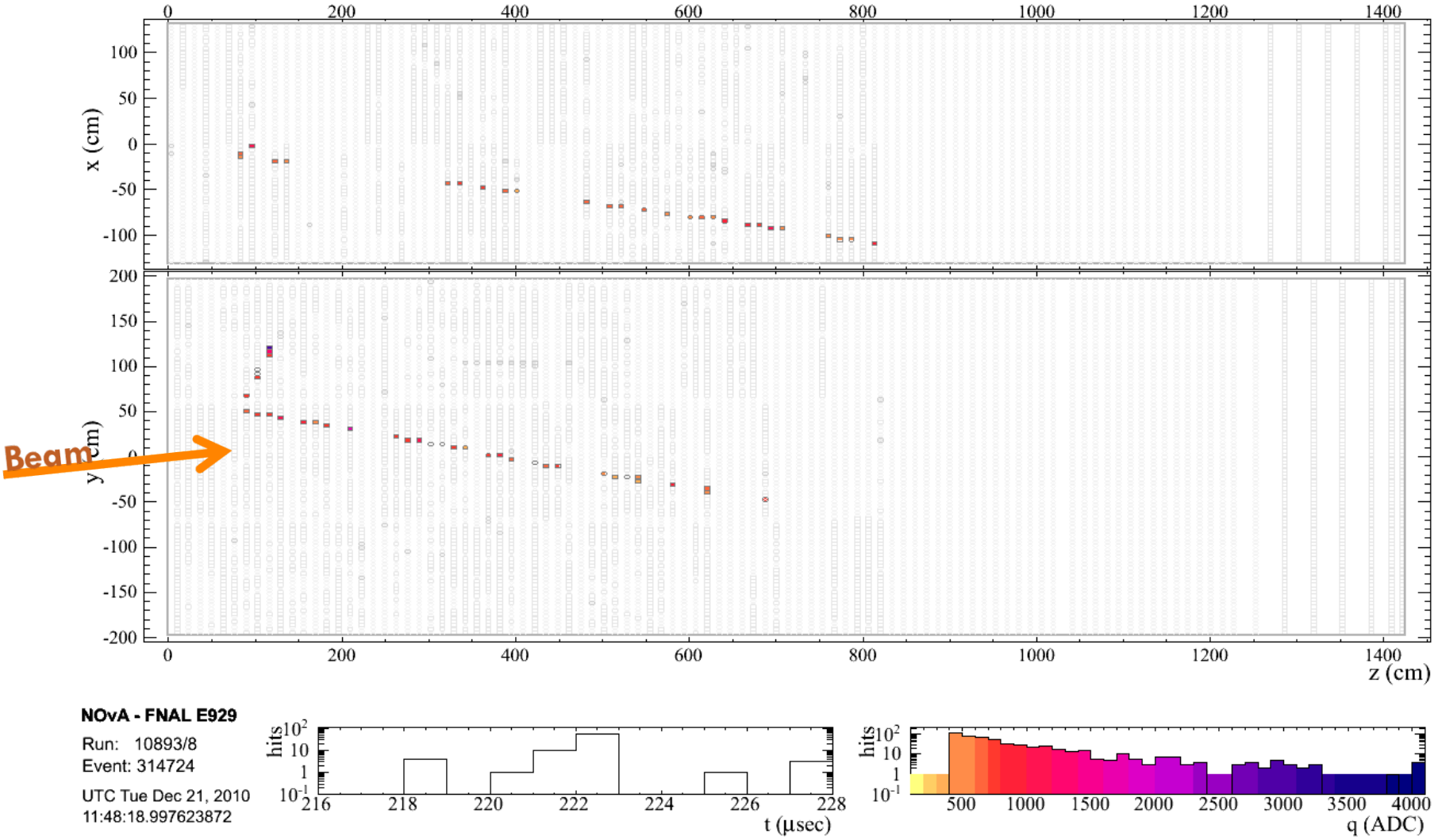
Finding Booster Neutrinos



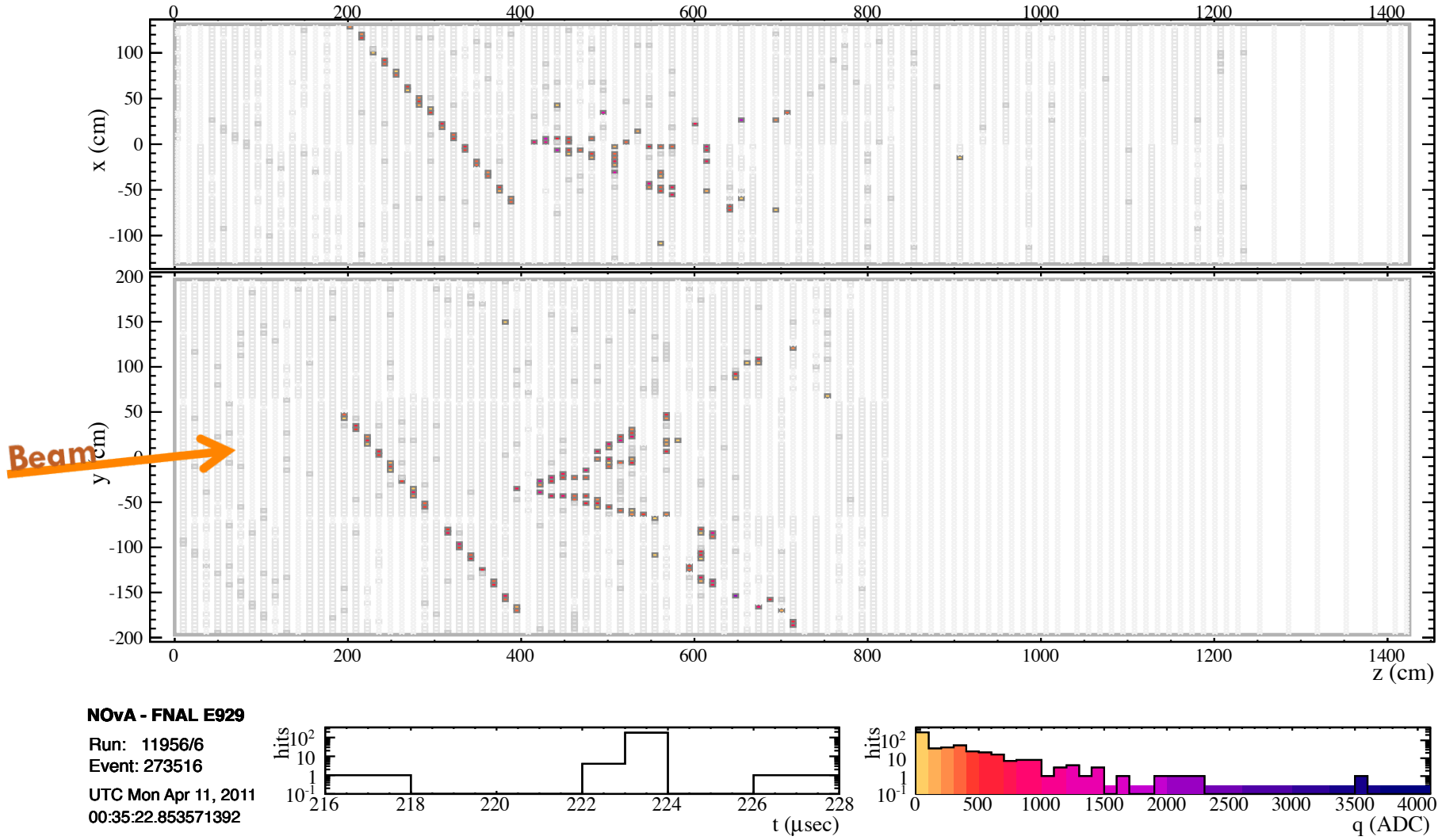


- NDOS nearly on Booster axis
- Detector rotated wrt axis
- 3×10^{19} POT, 222 booster events (92 cosmic BG)

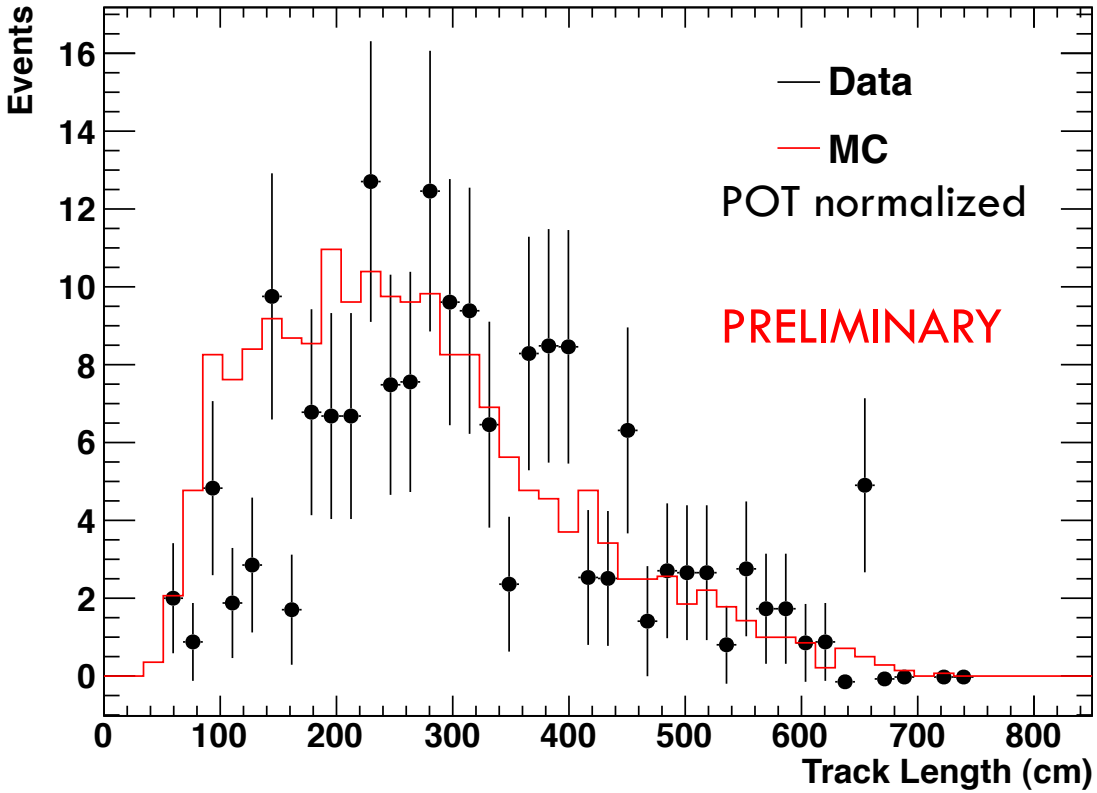
Neutrinos


x (cm)
y (cm)
z (cm)
Beam
NOvA - FNAL E929
Run: 10893/8
Event: 314724
UTC Tue Dec 21, 2010
11:48:18.997623872
hits
t (µsec)
hits
q (ADC)

Neutrinos


Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11956/6
Event: 273516
UTC Mon Apr 11, 2011
00:35:22.853571392
hits
t (µsec)
hits
q (ADC)

Comparisons to MC



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

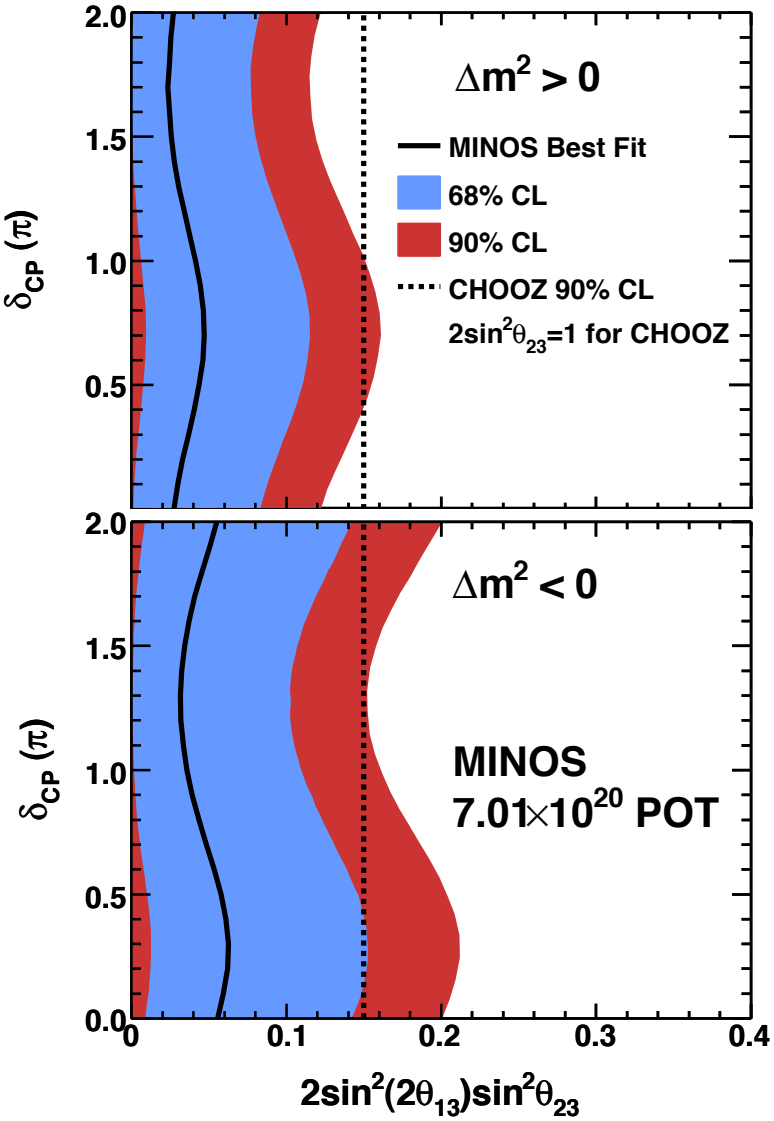
Summary

- 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^2, $\sin^2(2\theta_{23})$
- Far construction coming soon
- Near detector on the surface taking neutrino data now!

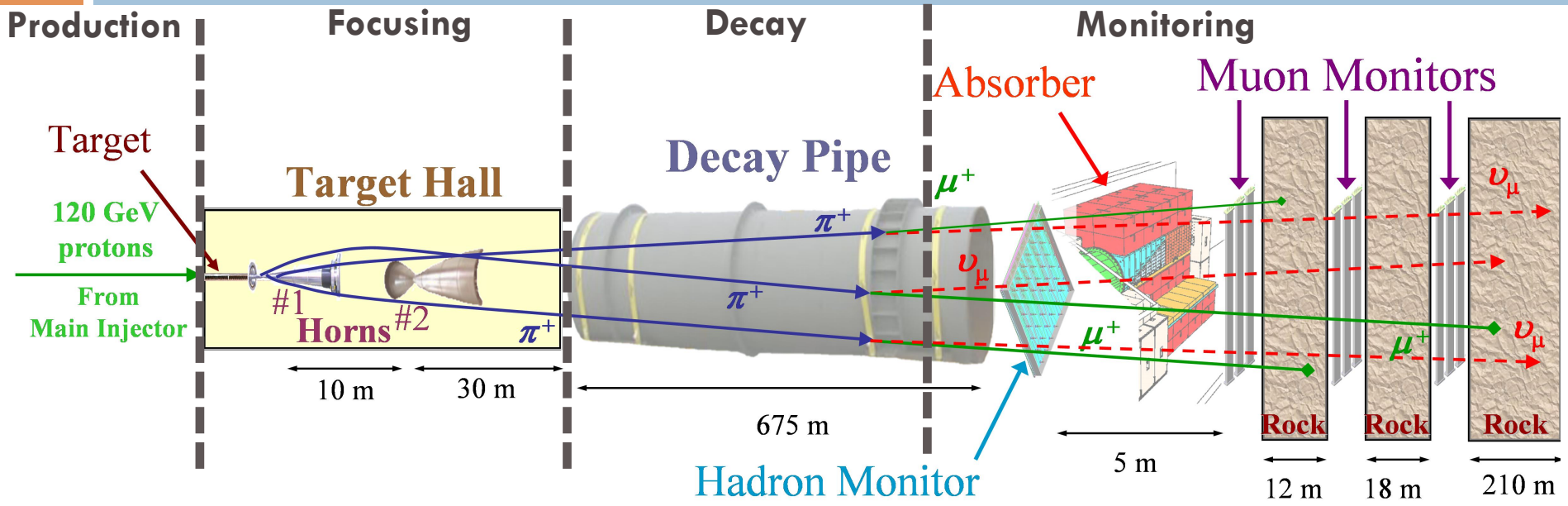
Backup Slides

Current Limits

- NOvA aims to improve limits by an order of magnitude
  - bigger detector
  - low Z, 65% active detector for improved event recognition
  - powerful beam
  - off-axis technique

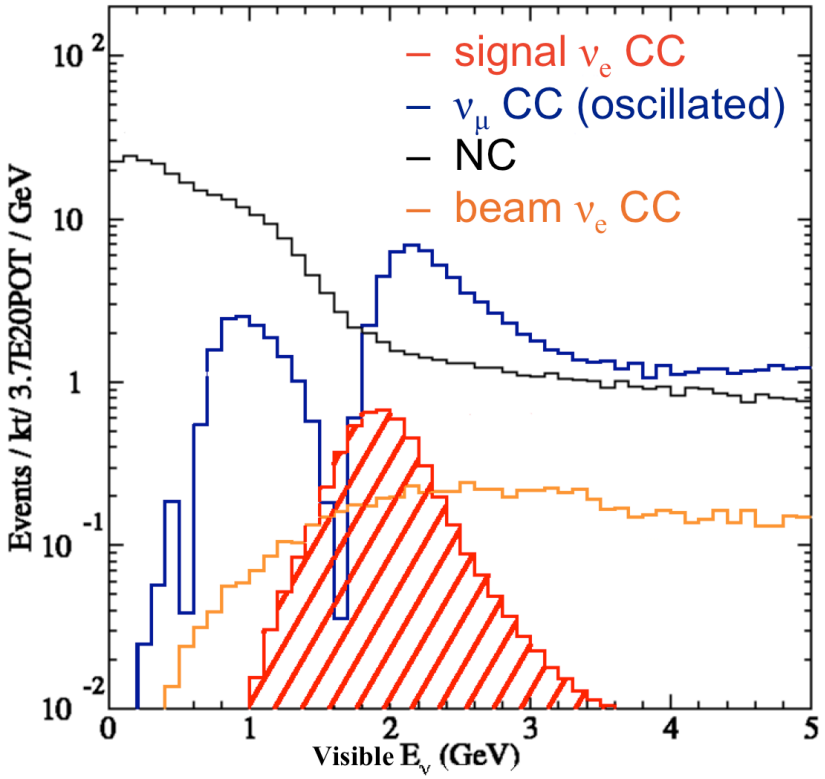


Making a Neutrino Beam



- **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

Case Study



Interaction Type	Events in 3 years
ν_μ CC	2500
NC	2200
ν_e CC beam	120
ν_e CC signal	270

- Consider ν_e appearance at the CHOOZ limit:
  - Before cuts, signal is 4σ above background
  - Cuts on summed event pulse height, event length: 7σ
  - Sophisticated selection based on event topology: 18σ
  - Compare to ~4σ of MINOS analysis

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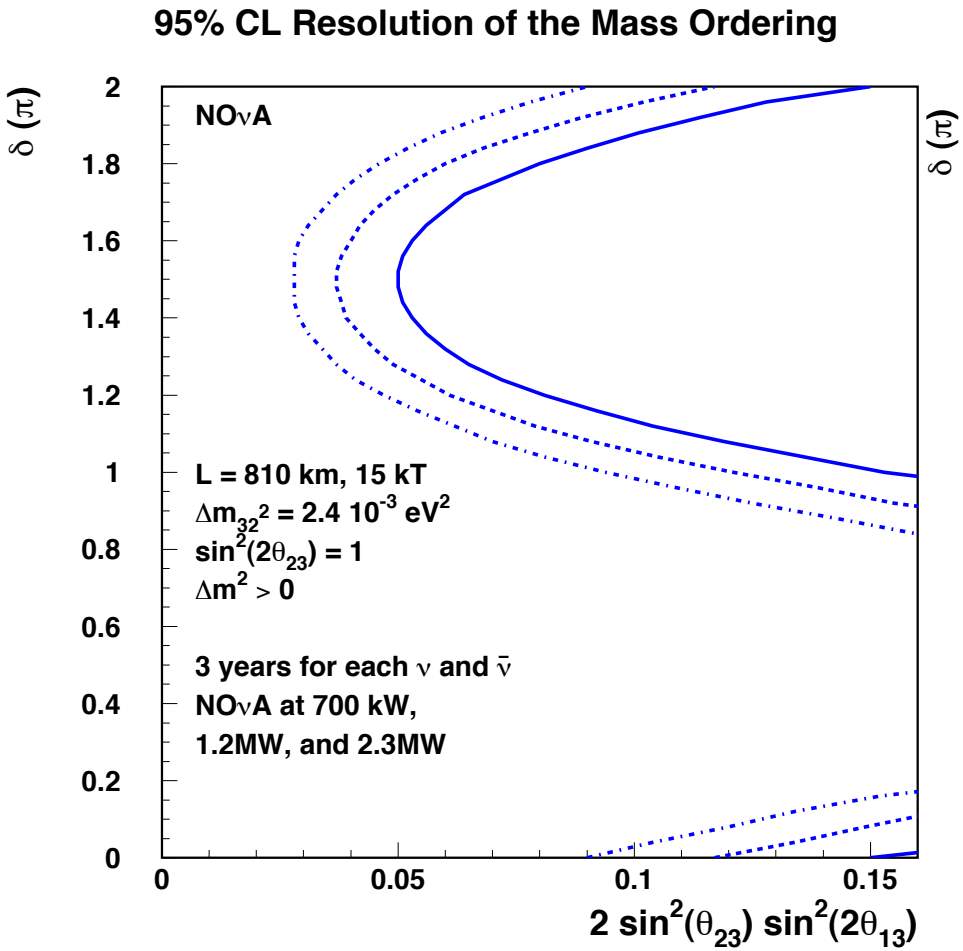
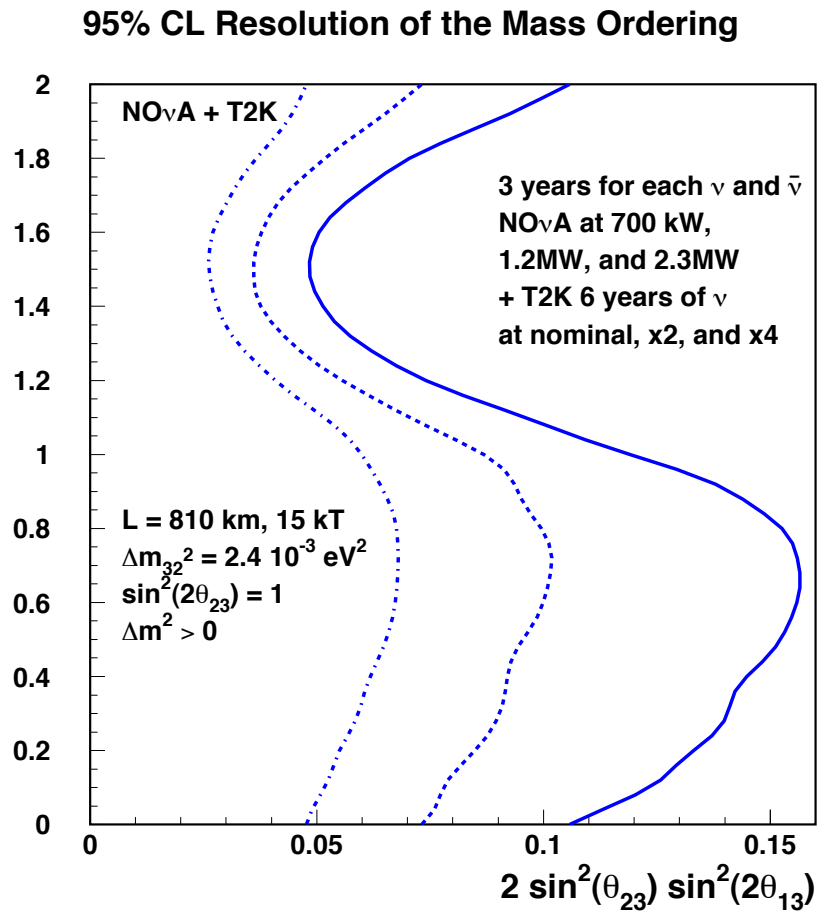
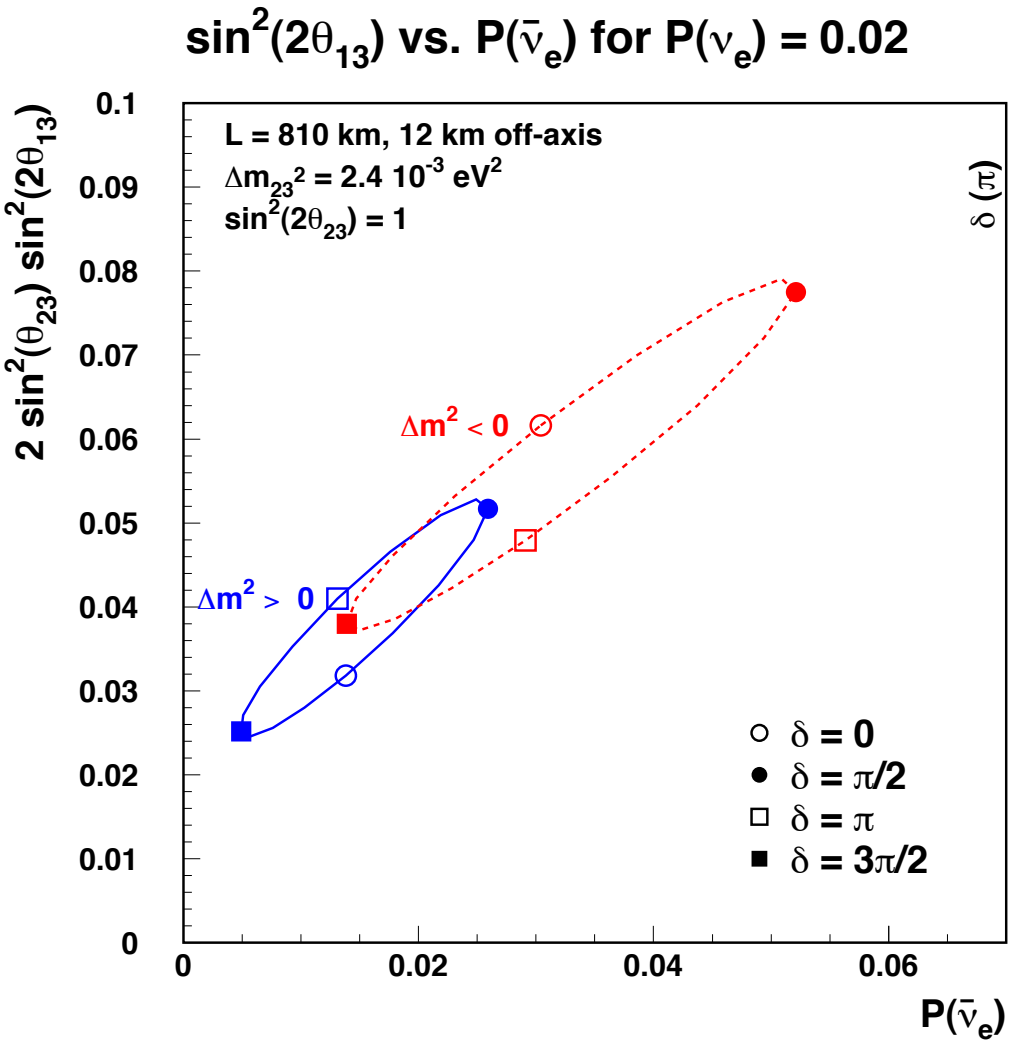
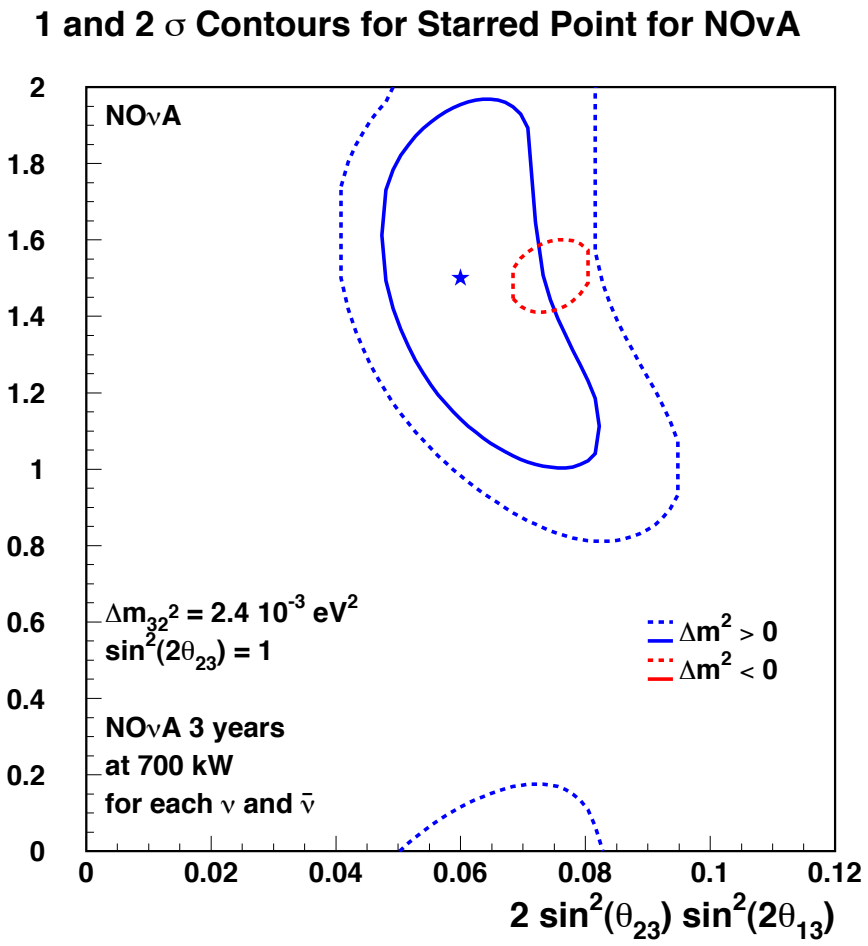
Mass Hierarchy



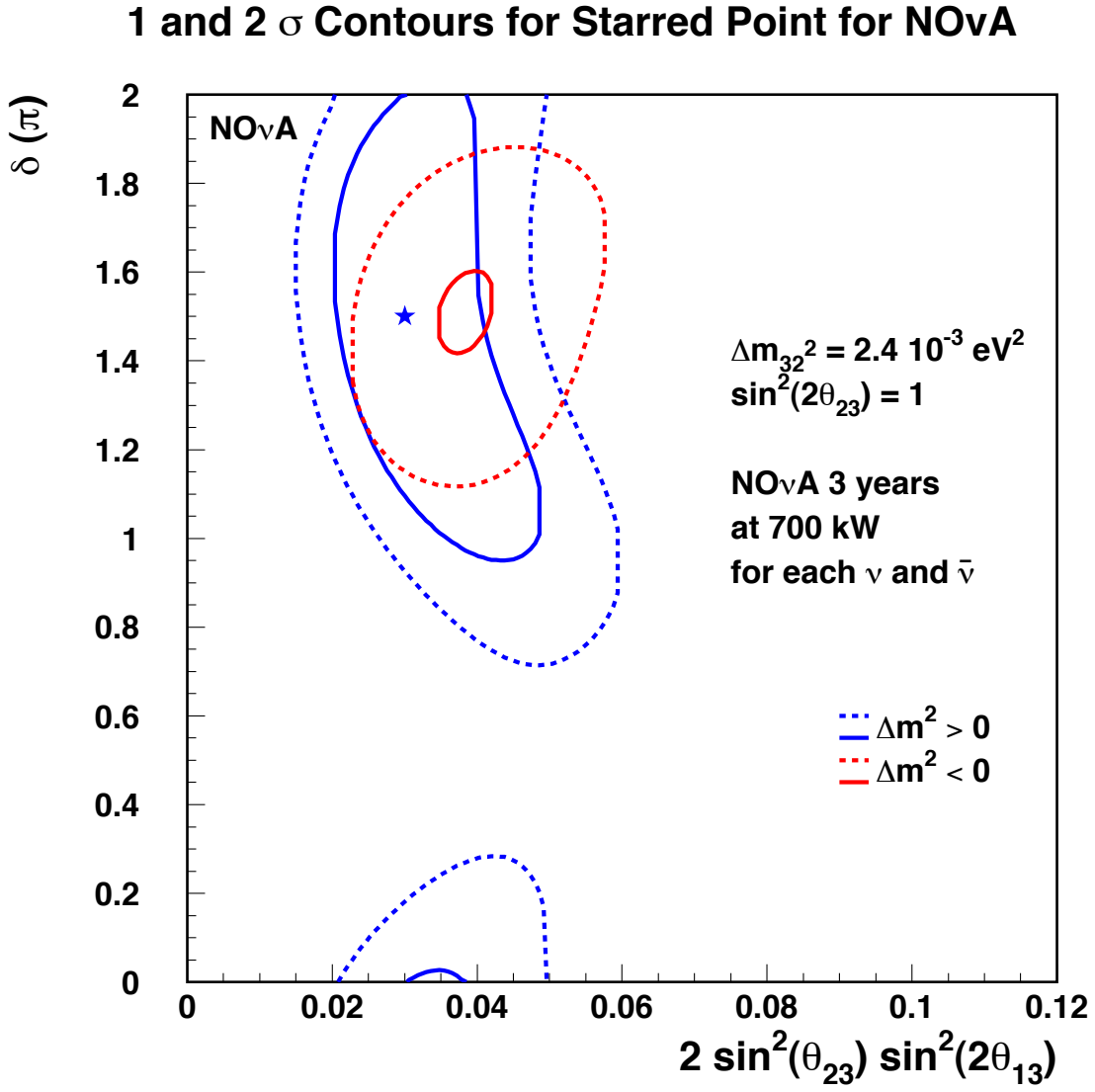


Sensitivity to Hierarchy





Example of Constraining CP



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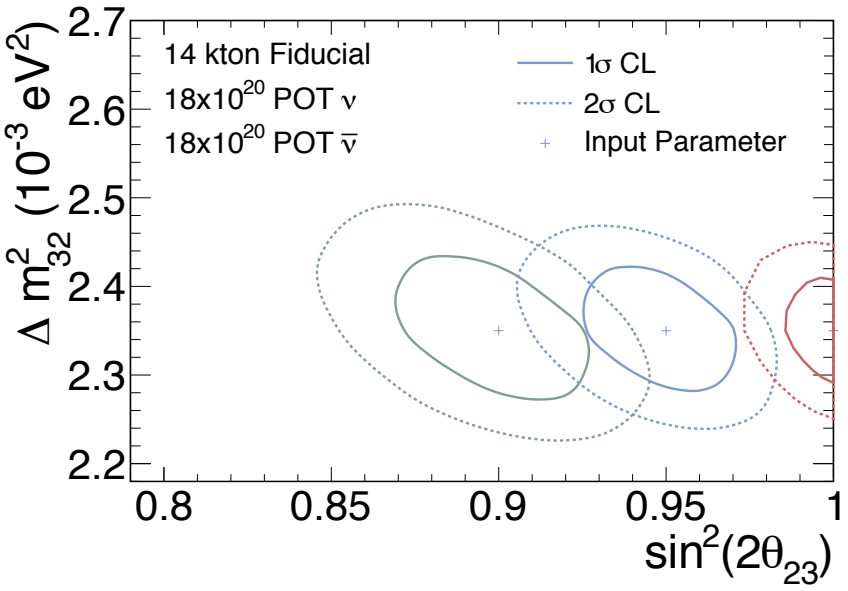
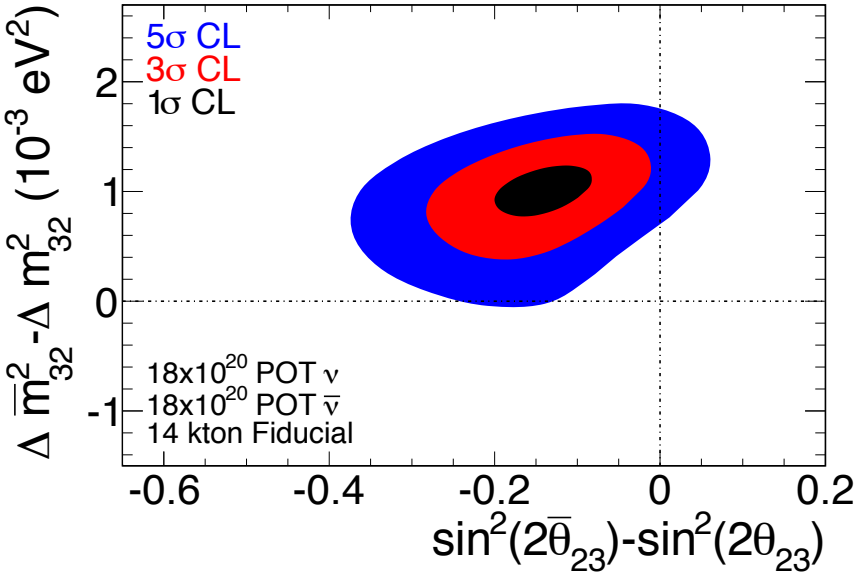
Muon Neutrino Disappearance





- Sensitivity to (Δm^2, $\sin2(2\theta_{23})$) after 3 years each of neutrino beam and antineutrino beam
- If tension in MINOS neutrino/ antineutrino results persists, the difference in the neutrino and antineutrino parameters measured by nova

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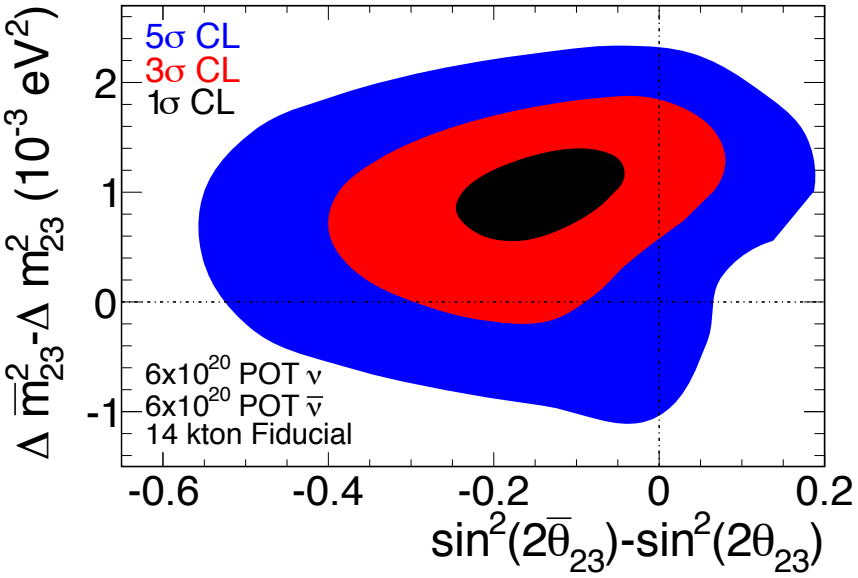
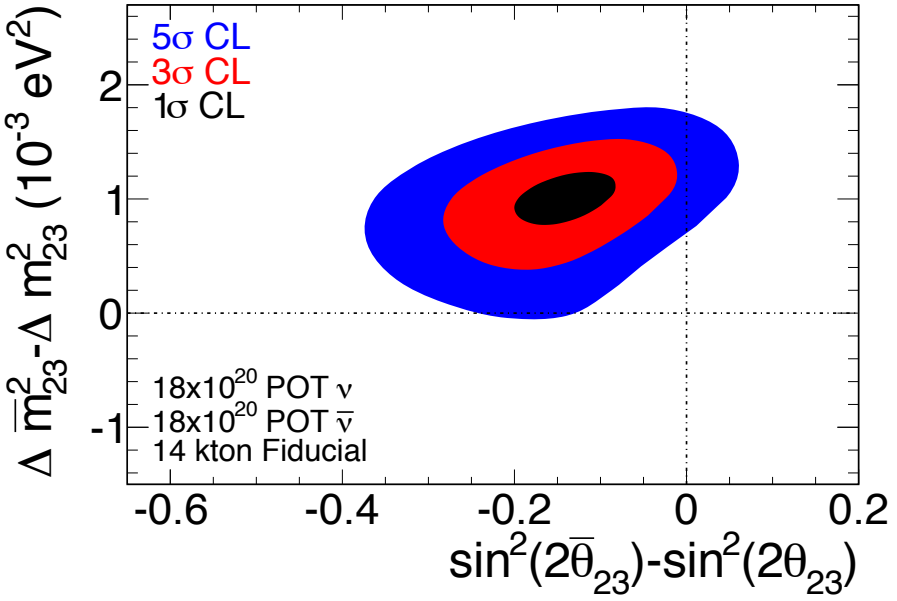
Muon Neutrino/Antineutrino Disappearance



1 Year Each

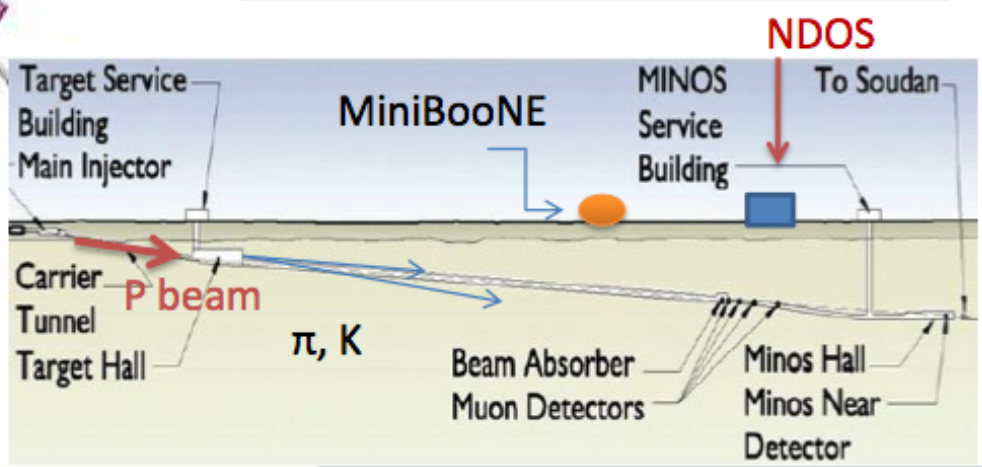
3 Years Each



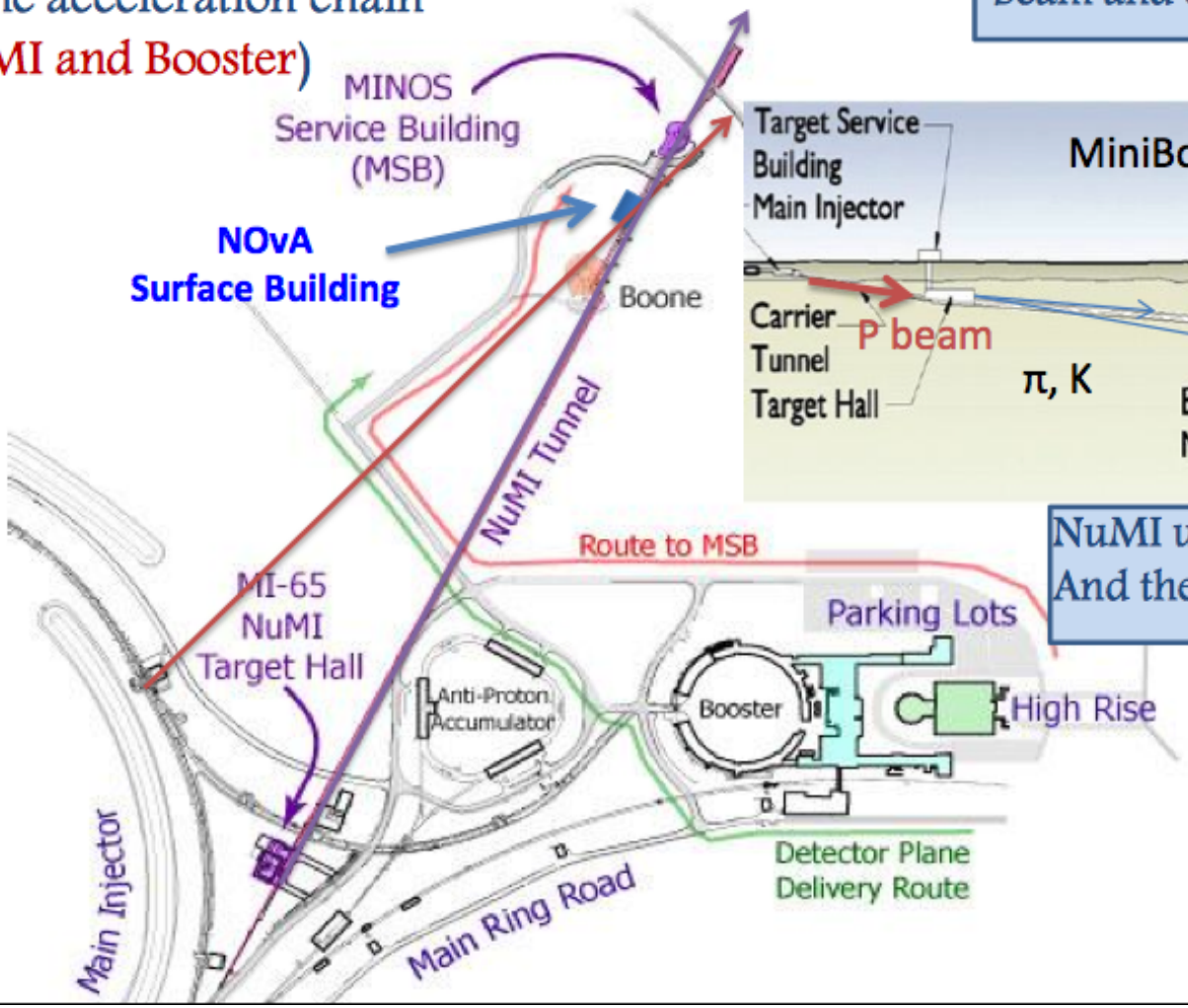
Where is NDOS?

Beams are produced at two different stages on the acceleration chain (NuMI and Booster)

NDOS is ~6.1° off axis of the NuMI beam and on axis of the Booster



NuMI uses 120 GeV protons
And the Booster uses 8GeV protons



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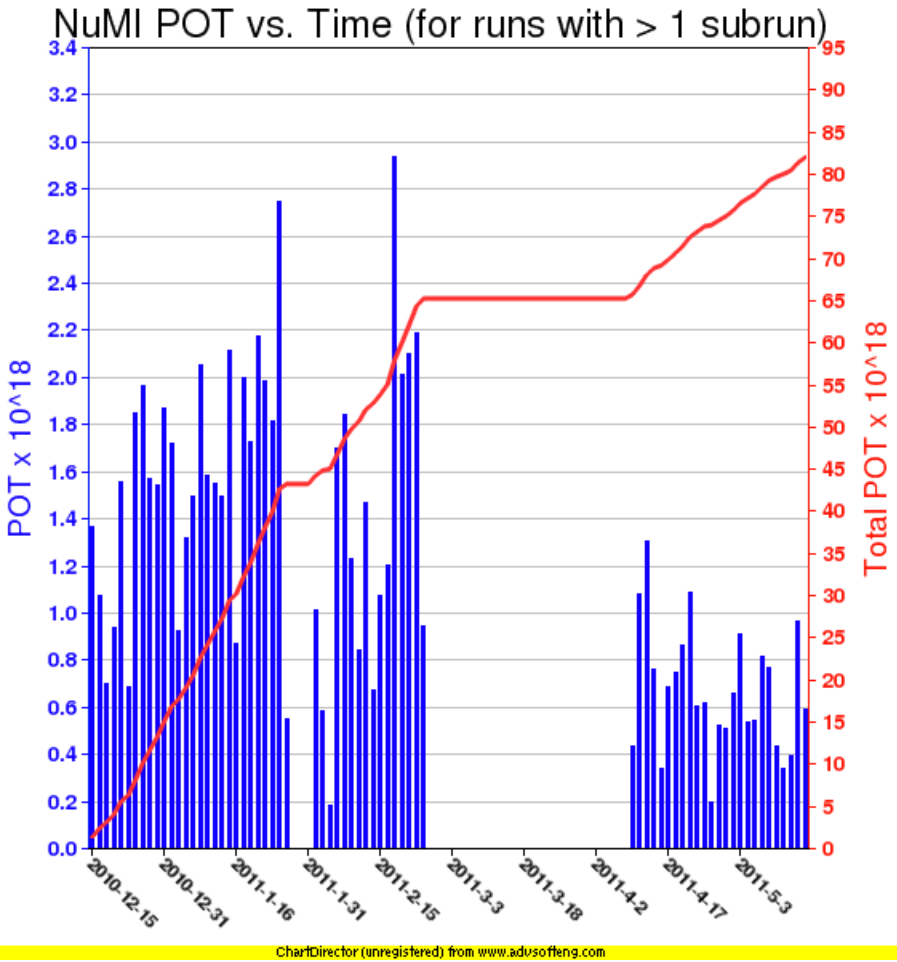
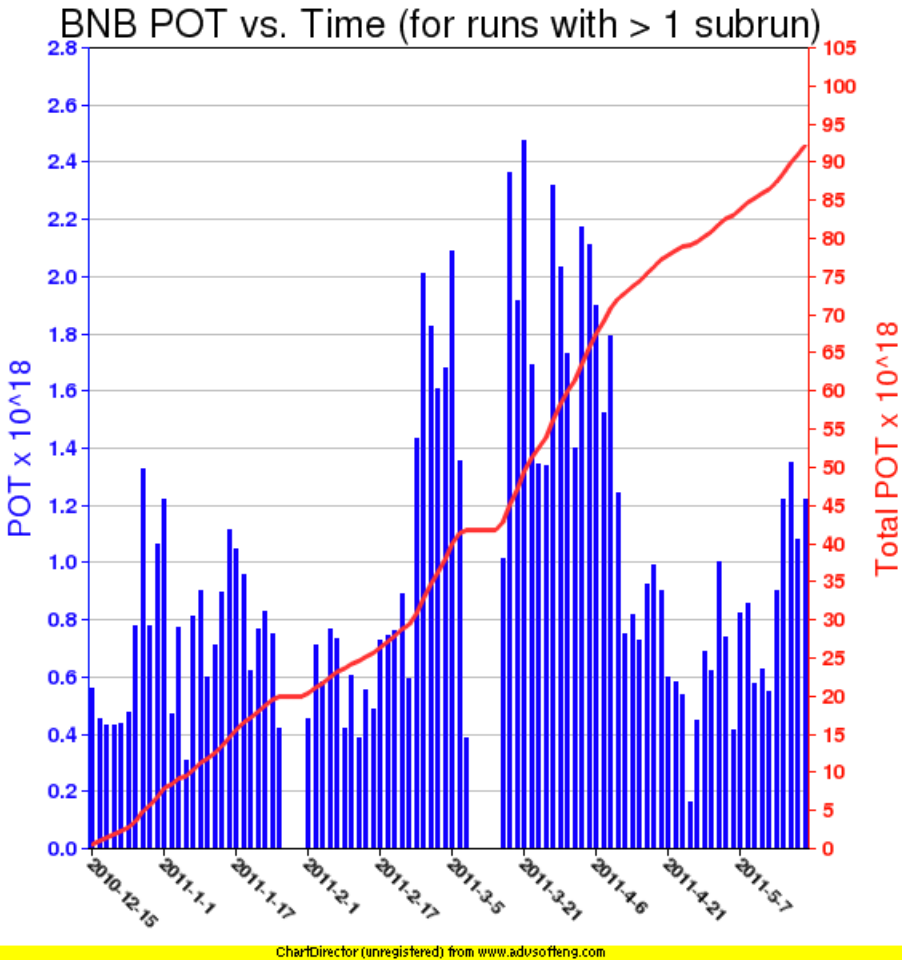
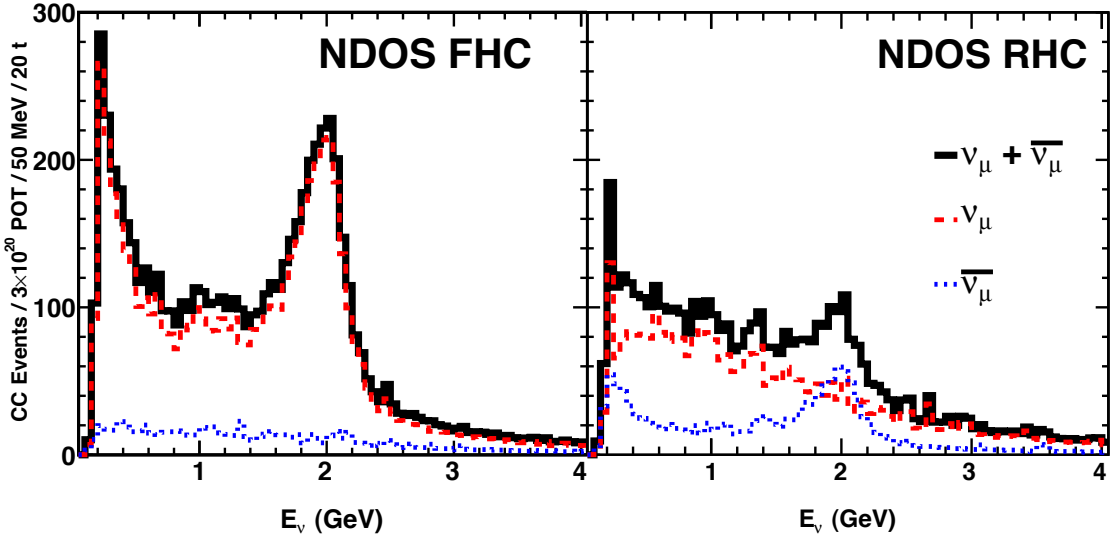
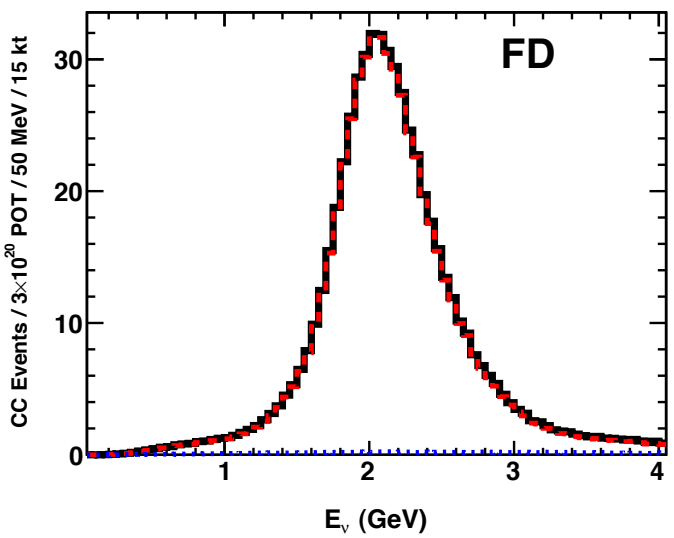
POT Accumulated

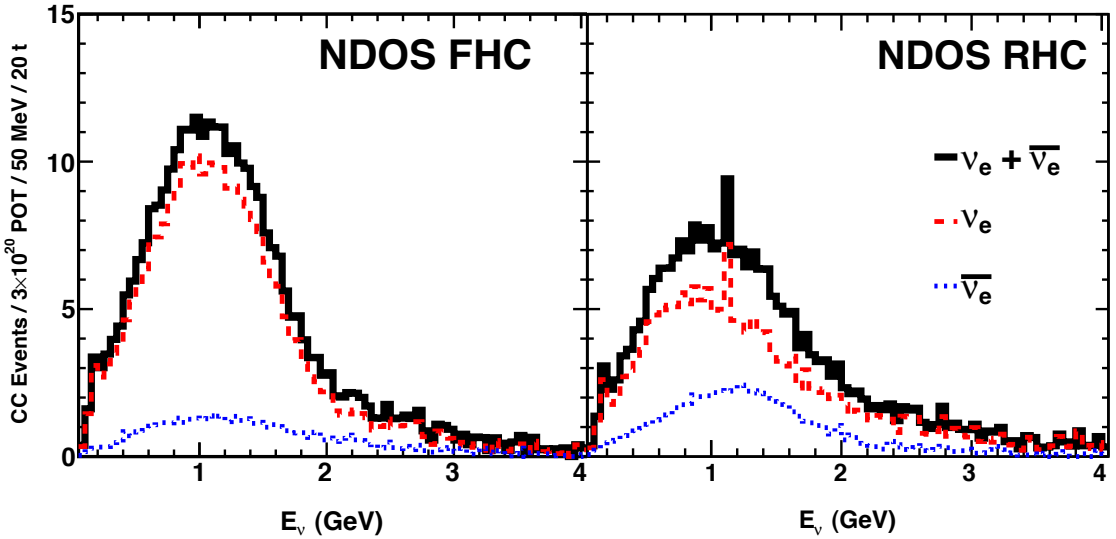


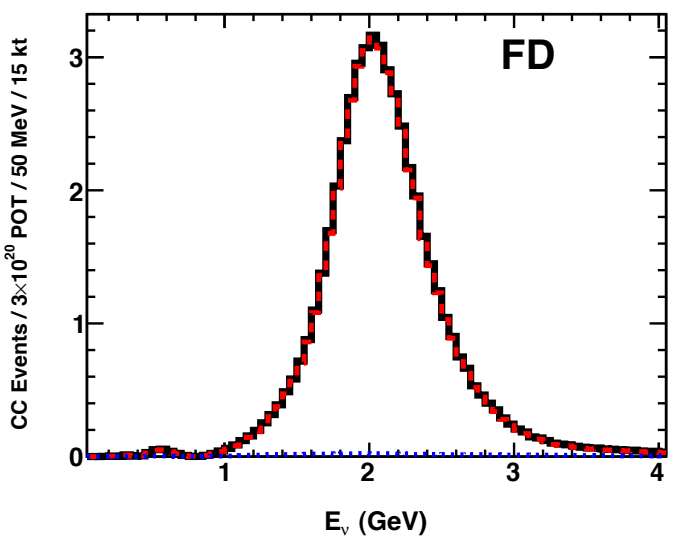


NDOS Energy Spectrum



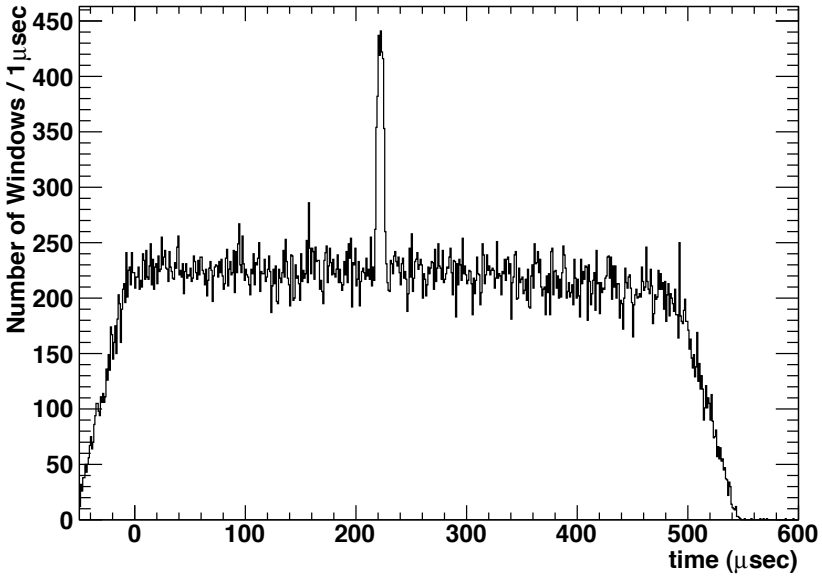


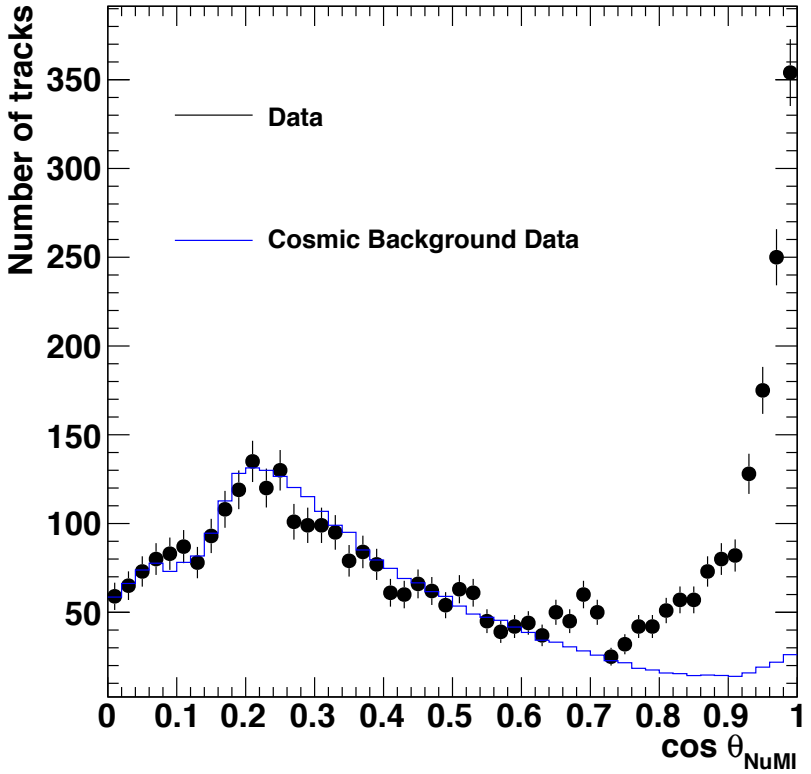




Finding NuMI Neutrinos

- 110 mrad off NuMI axis

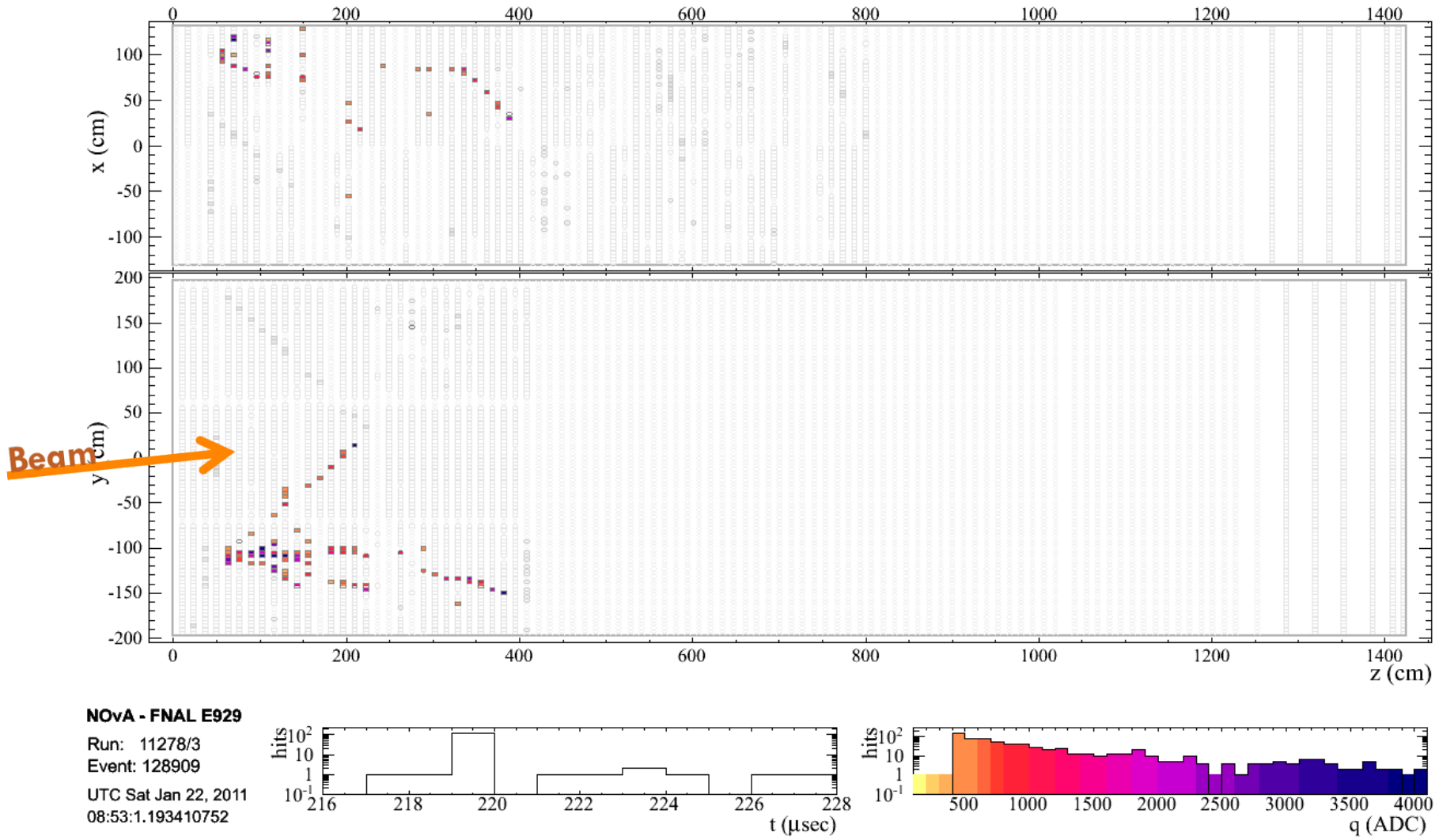




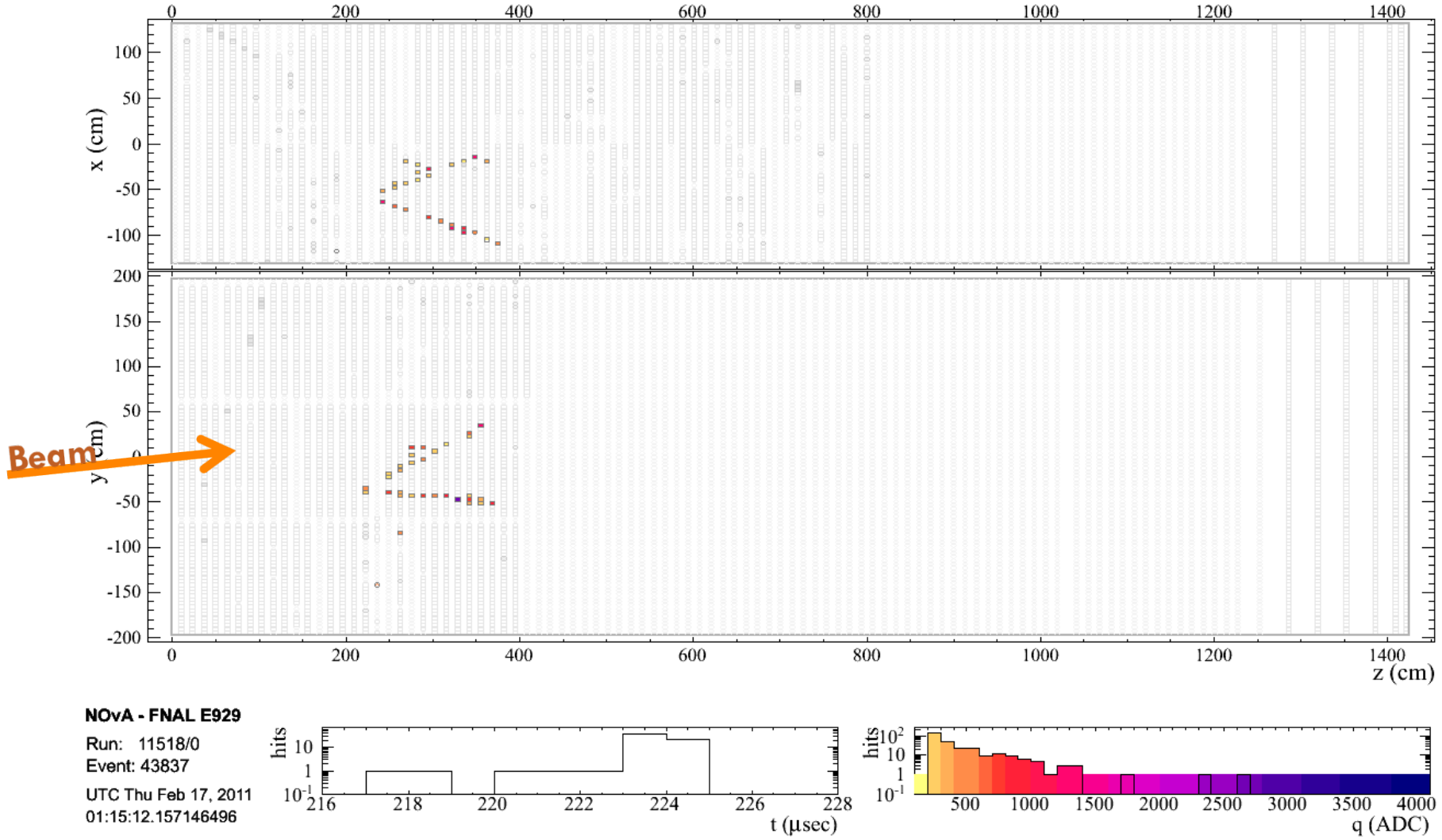
Reverse Horn Current Mode 5.6×10^{19} POT	NuMI ν's	BG
Fiducial Events	1001	69
Fully Contained	184	12

Forward Horn Current Mode 8.4×10^{18} POT	NuMI ν's	BG
Fiducial Events	253	39
Fully Contained	36	12

Neutrinos


Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11278/3
Event: 128909
UTC Sat Jan 22, 2011
08:53:1.193410752
hits
t (μsec)
hits
q (ADC)

Neutrinos


Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11518/0
Event: 43837
UTC Thu Feb 17, 2011
01:15:12.157146496
hits
t (μsec)
hits
q (ADC)