NOνA Experiment

Jarek Nowak
University of Minnesota
For NOvA Collaboration

PANIC11

RUTHERFORD CENTENNIAL

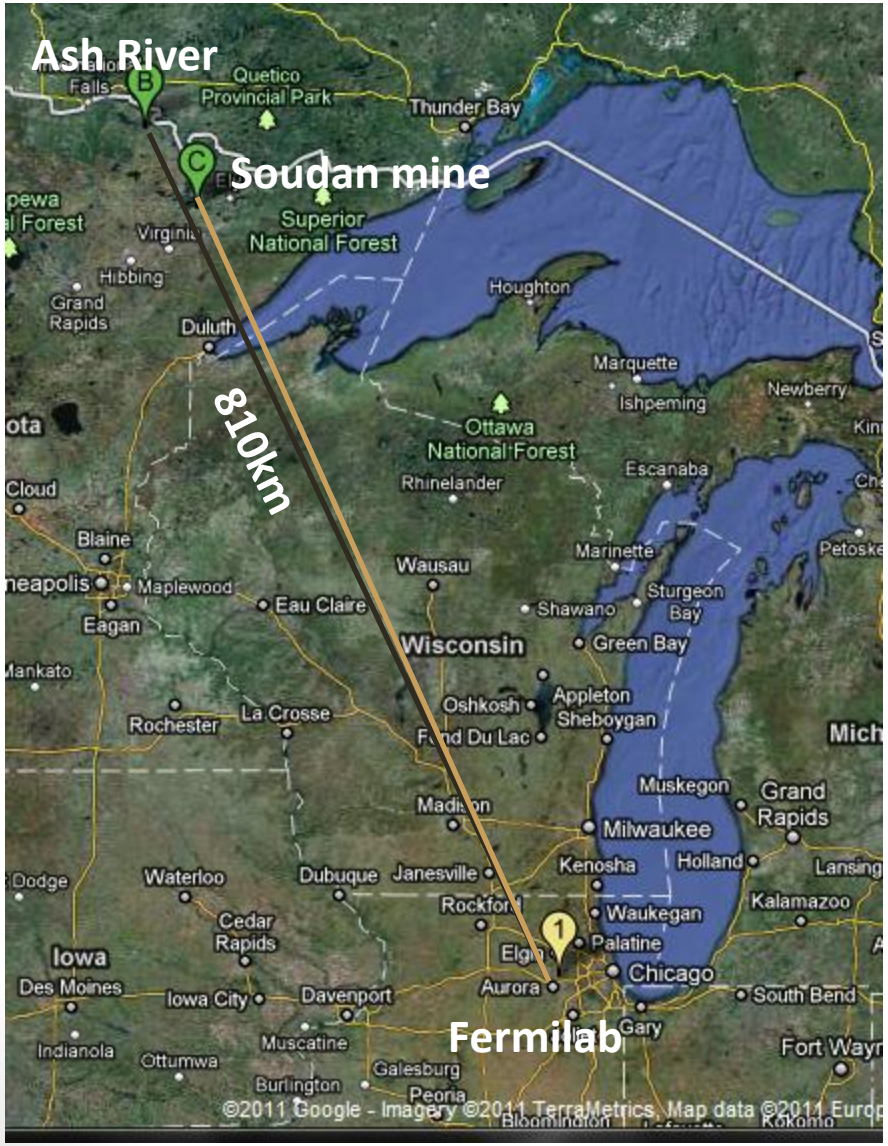
NOvA Collaboration

140 Collaborators

24 Institutions

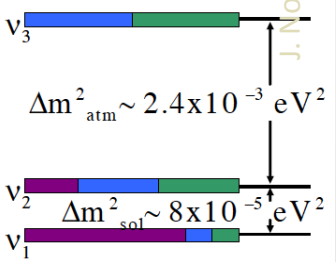
4 Countries

NuMI off-axis ν_e Appearance Experiment



- 810 km long baseline.
- Two detectors 14 mrad off the beam axis.
- Near detector at fermilab 1 km from target.
- Far detector in Ash River, MN.
- NuMI beam upgraded to 700 kW.

- Search for ν_e appearance and ν_μ survival to measure:
  - θ_{13}
  - **Mass hierarchy**

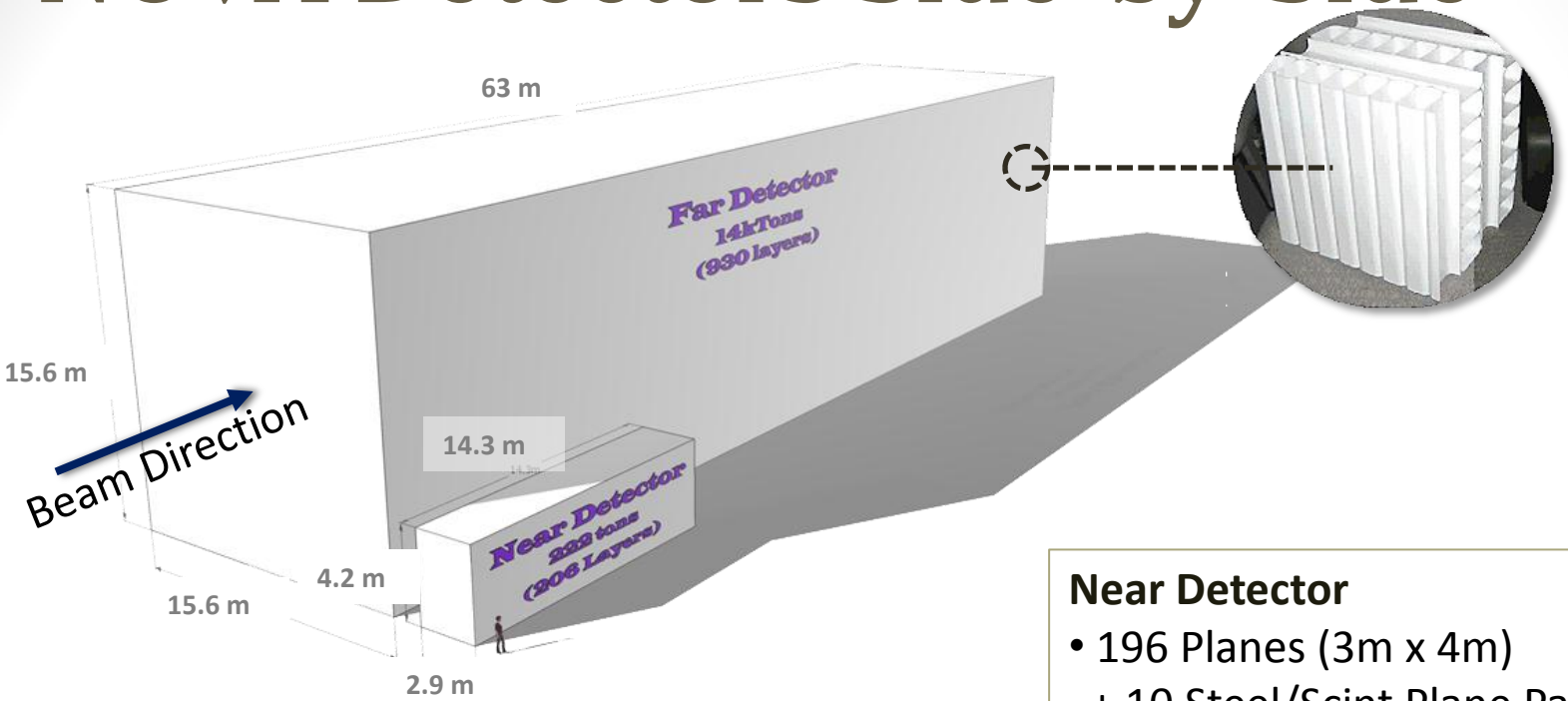


  - **Constrain CP violation phase**
  - Θ_{23}, Δm^2_{32}

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

NOνA Detectors Side-by-Side



Far Detector

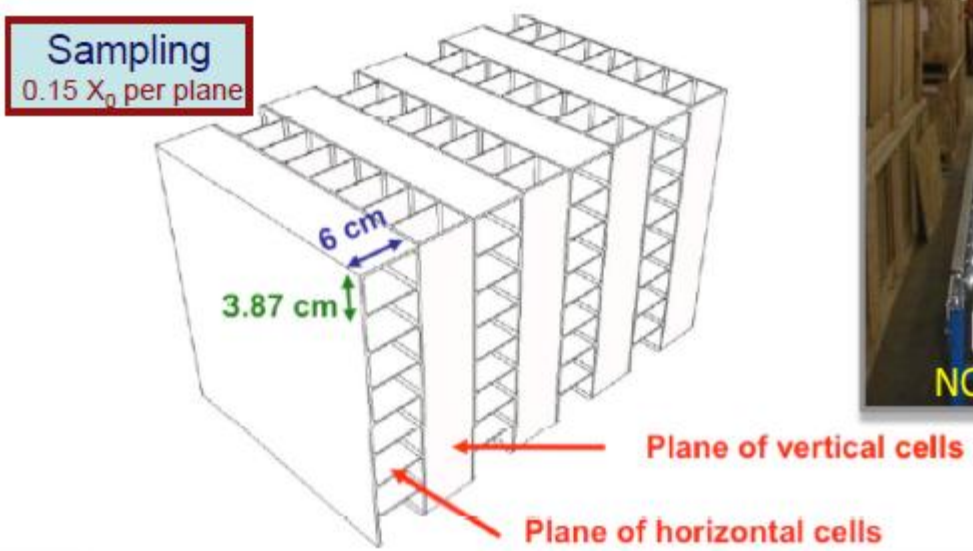
- 930 Planes (15.6 m x 15.6 m)
- 14kTon
- 360000 cells
- Cosmic Ray Muon Rate:
  - ~200 kHz (2-3 m overburden)
- In-Spill Rate
  - **1400 ν_e beam events/year**

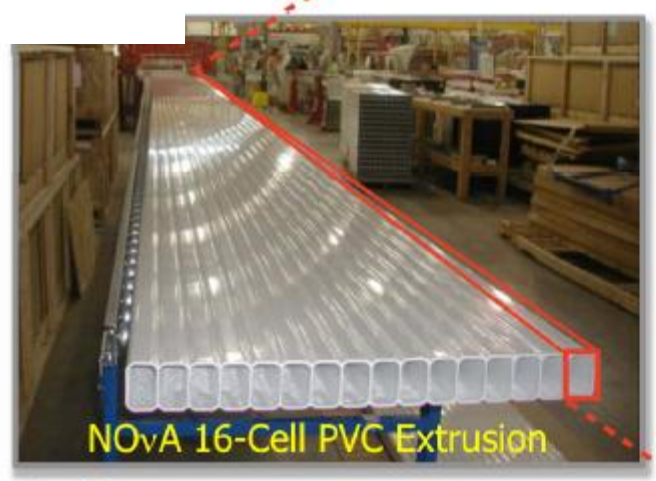
Near Detector

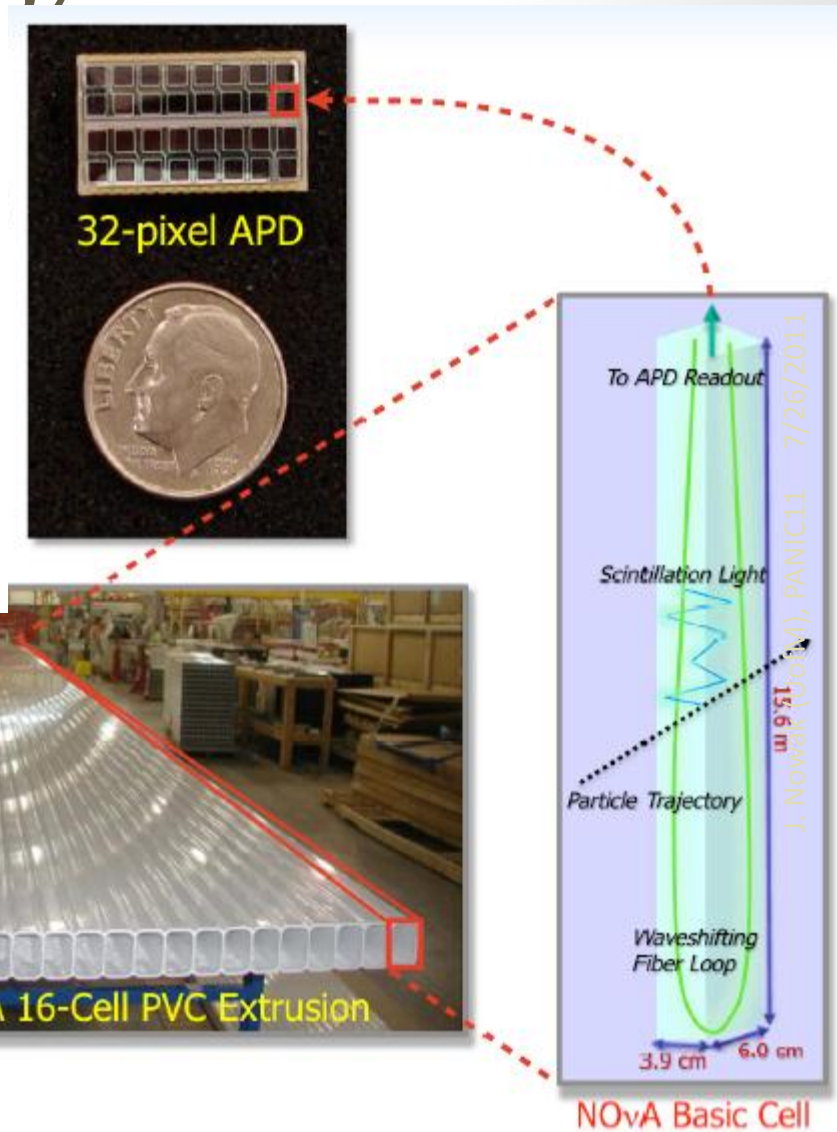
- 196 Planes (3m x 4m)
  + 10 Steel/Scint Plane Pairs ("Muon Catcher")
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
  - ~50 Hz (105 m overburden)
- In-Spill Rate:
  - 10 μs duration every 1.33 s
  - **30 neutrino events/spill**

Detector Technology

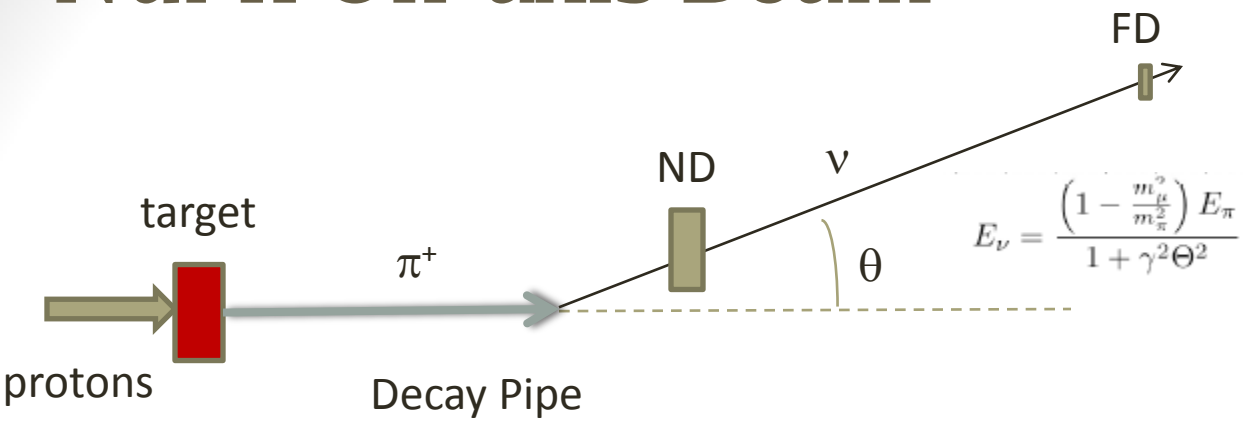
- Detectors composed of highly reflective PVC extrusions
- Filled with liquid scintillator (mineral oil + 5% pseudocumene)
- Each cell readout by a wavelength shifting fiber onto one pixel of a 32-pixel avalanche photodiode (APD)
  - 30 PE from far end of cell into APD for MIP
- Num cells: 360000 (Far), 16000 (Near)



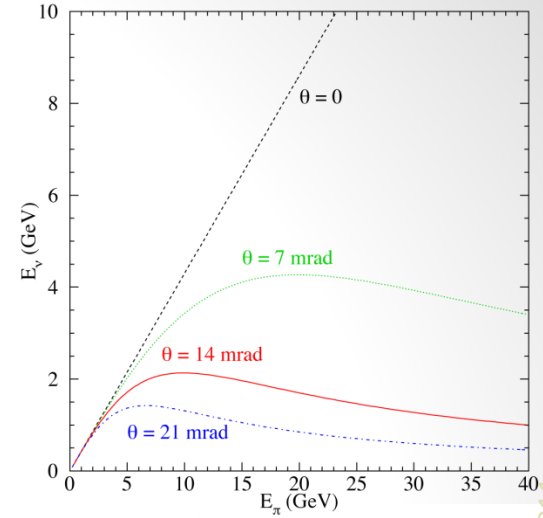




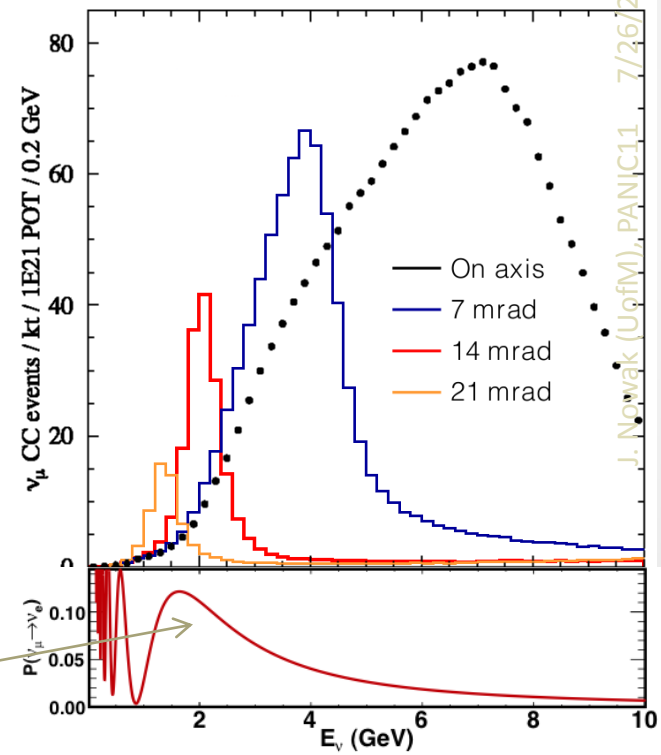
NuMI Off-axis Beam



$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_\pi^2}\right) E_\pi}{1 + \gamma^2 \Theta^2}$$



- **Enhanced 700 kW NuMI beamline**
- **Reduce cycle time from 2.2 to 1.3 seconds.**
- **Increased intensity/cycle with additional Booster batch.**
- **New horn and target.**
- **10μs beam pulse every 1.3 seconds**
- **4.9e13 POT/pulse or 6e20 POT/year**



- **Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam. Close to the oscillation maximum.**

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 go into ν_e

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

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

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

'solar' term is less < 1%

- If CP violation phase $\delta_{CP} \neq 0$ part of the interference term is asymmetric to $\nu \Leftrightarrow \nu$

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

Neutrinos(-)

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

Antineutrinos(+)

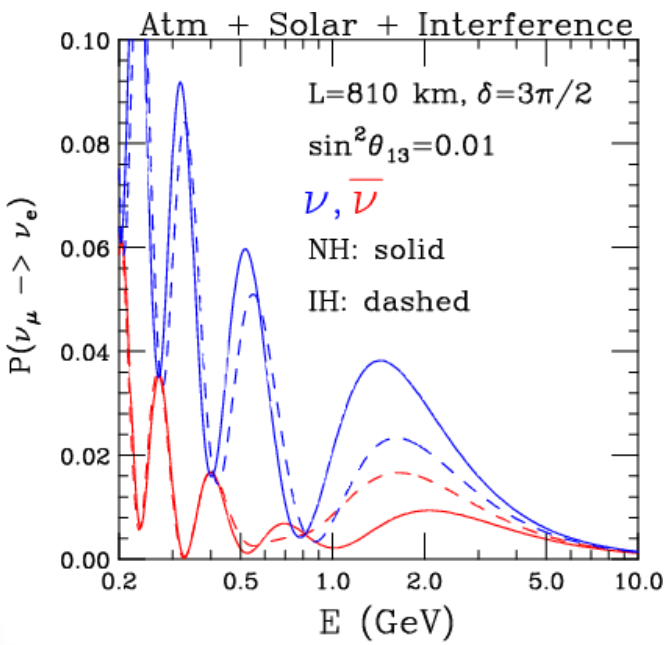
ν_e Appearance with MSW effect

- With 810 km baseline neutrinos will travel through the Earth crust.
- Due to flavor content of the surrounding matter there is an additional term in the Hamiltonian only for ν_e.

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

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

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

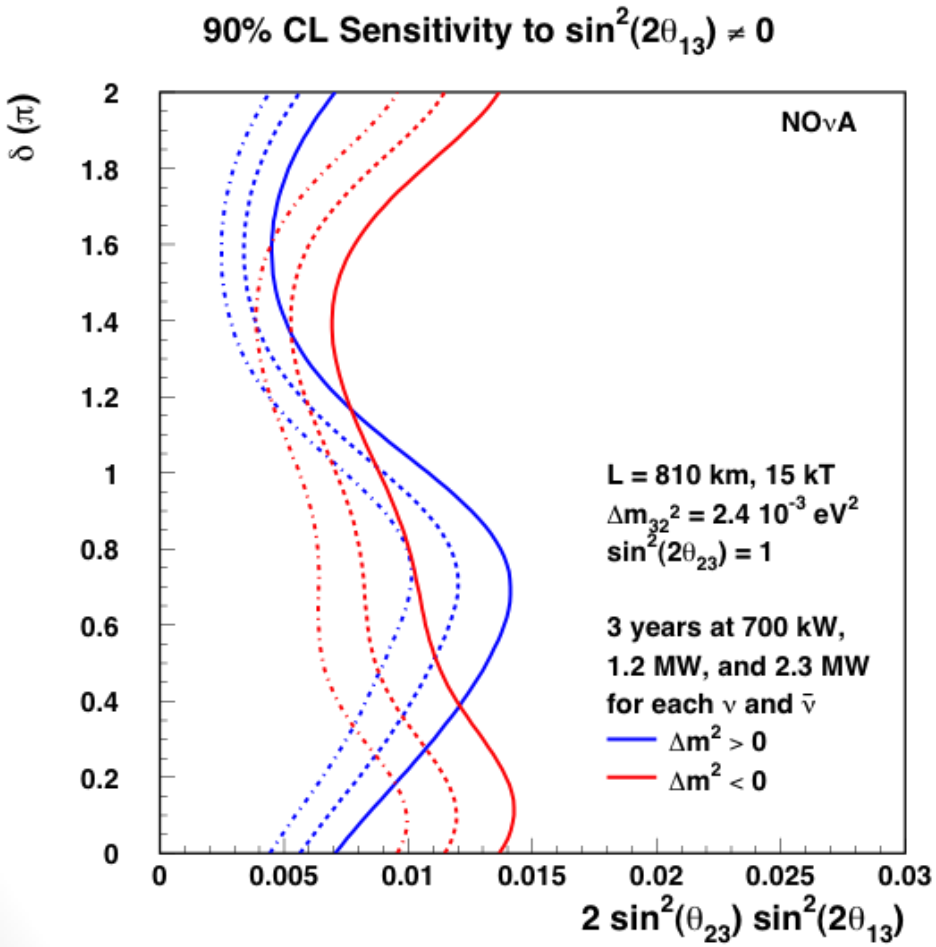


From S. Parke, "Neutrino Oscillation Phenomenology"
in Neutrino Oscillations: Present Status and Future Plans

Oscillation probability depends on sign of Δm^2

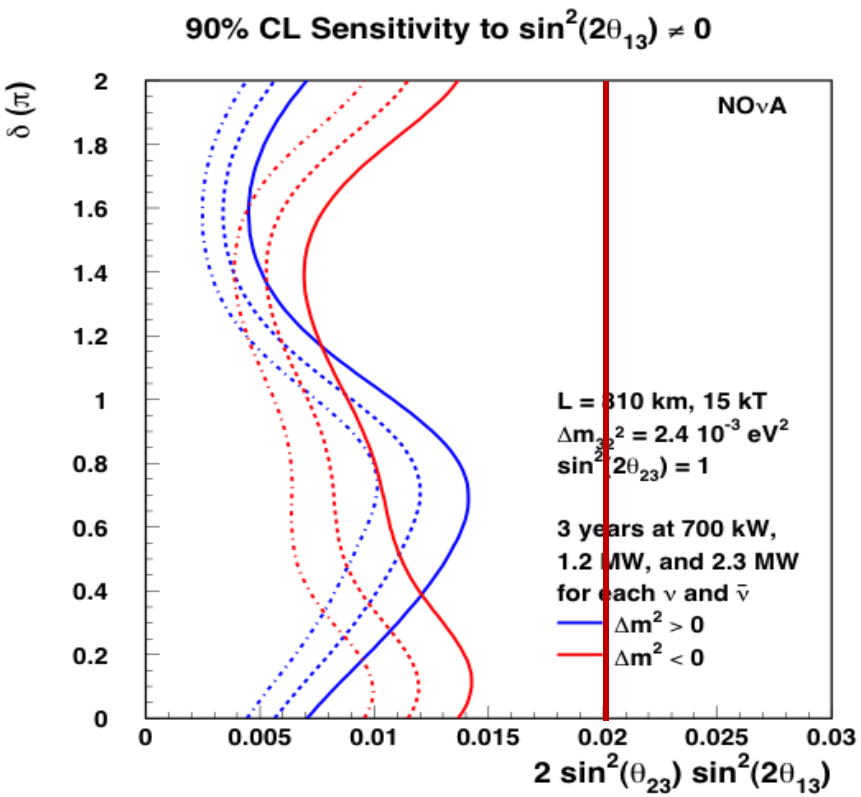
Oscillation probability modified by about 30% for NOvA

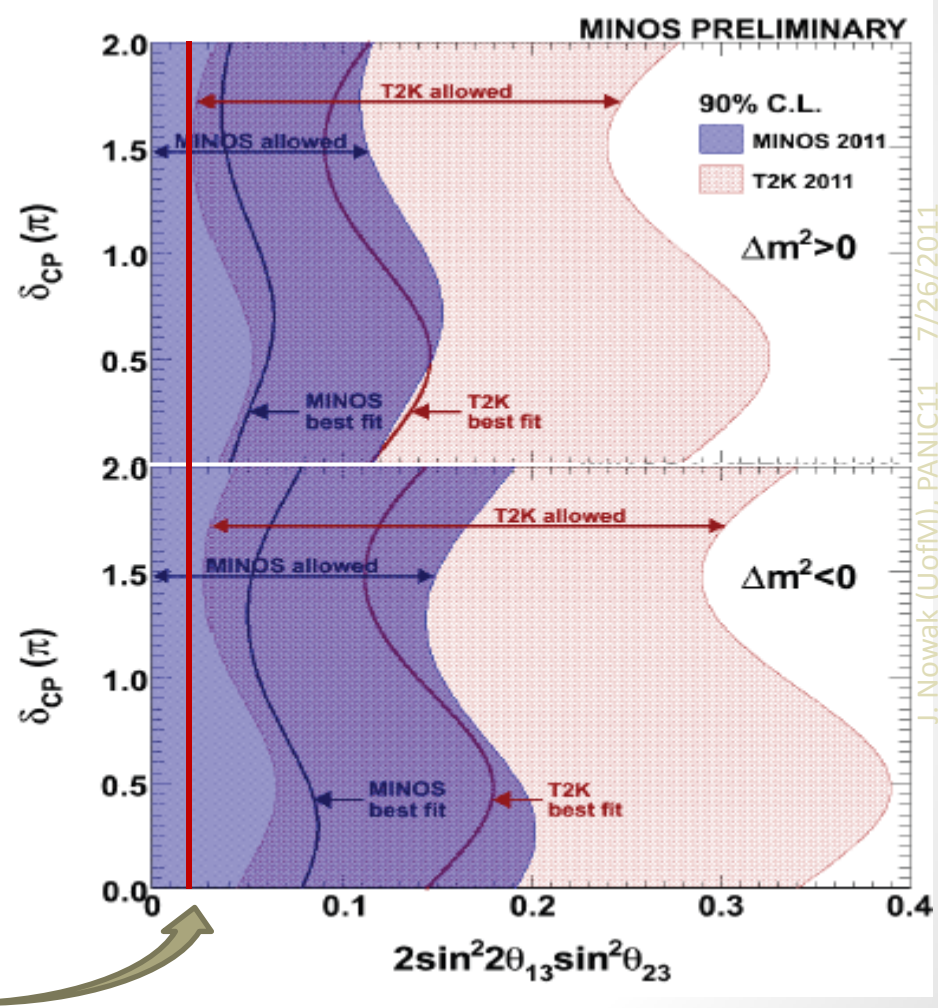
Sensitivity



- Sensitivity to $\sin^2(2\theta_{13})$ after 3 years each of neutrino beam and antineutrino beam in case of **normal** and **inverted** hierarchy
- 18e20 PoT in each neutrino and antineutrino mode

Comparing to recent results





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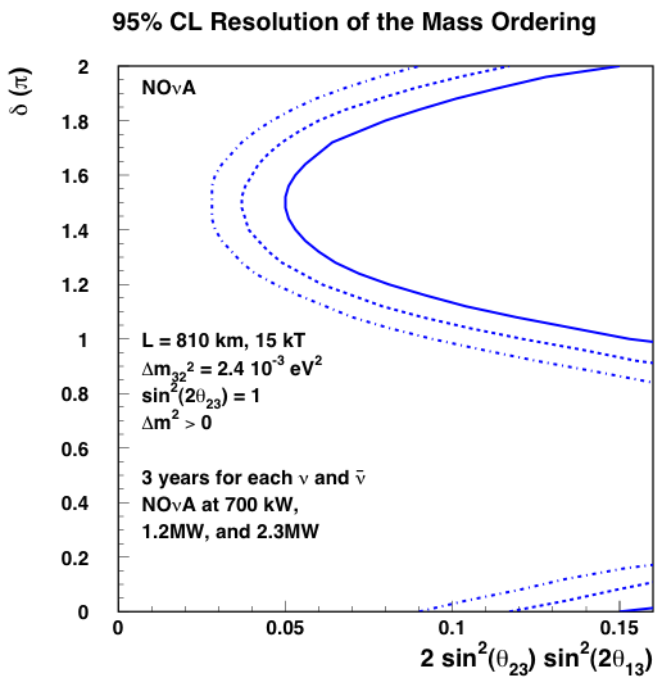
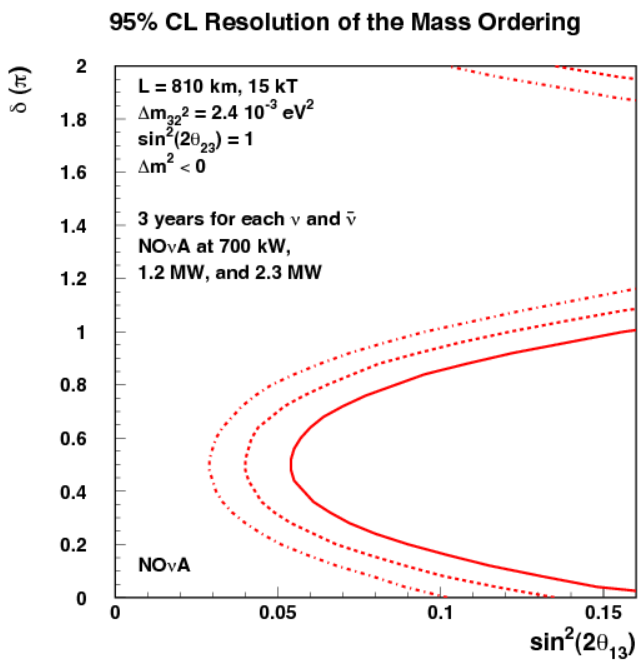
Resolution of the mass hierarchy

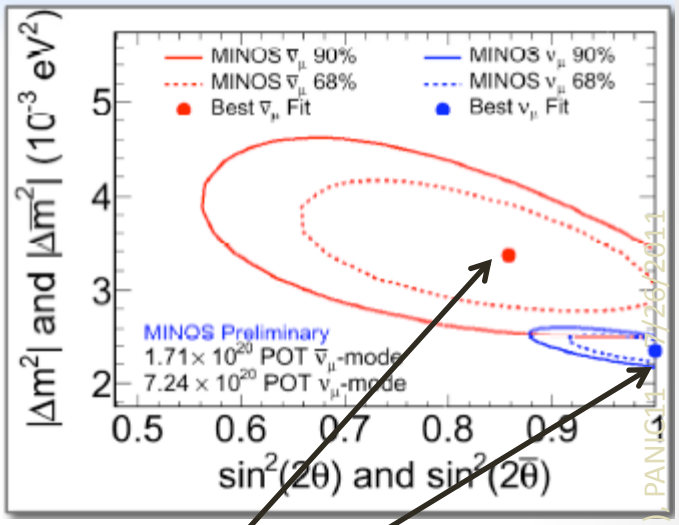
- Resolution of the mass hierarchy after 3 years (18e20 PoT) each of neutrino beam and antineutrino beam in case of **normal** and **inverted** hierarchy.
- Comparing results from neutrino and antineutrino beams.

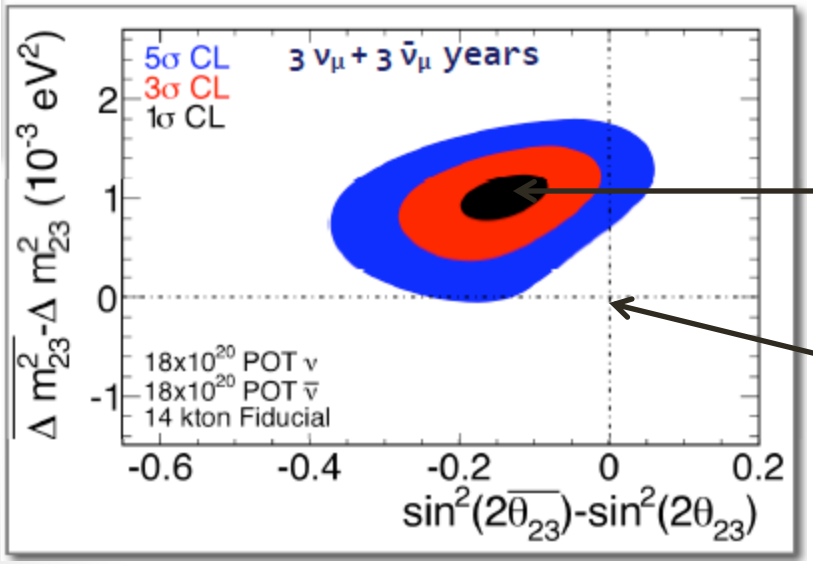




Neutrino and antineutrino parameters

- Minos reported 2σ difference between best fit values for neutrinos and antineutrinos.
- NOvA will be able to test this discrepancy at 3σ (5σ) CL after 1(3) year of running in each neutrino and antineutrino mode.

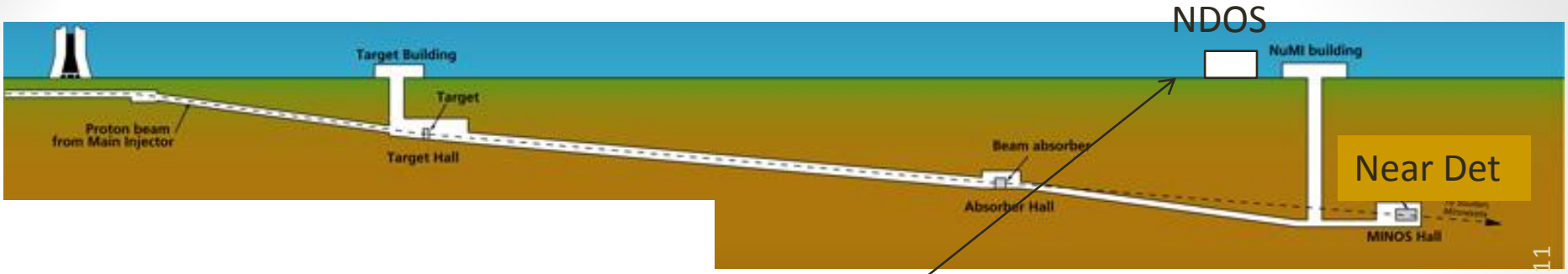




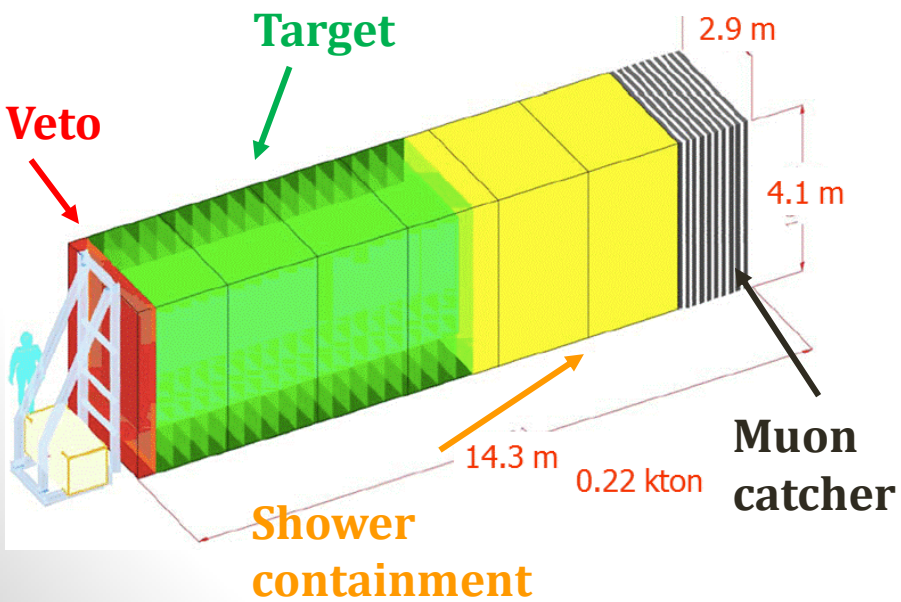
Difference between neutrino and Antineutrino MINOS results.

NULL HIPOTHESIS

NOνA Near Detector Prototype (NDOS)



- Prototype **N**ear **D**etector **o**n **S**urface (NDOS) – Taking Data Now!
- Identical to future Near Detector

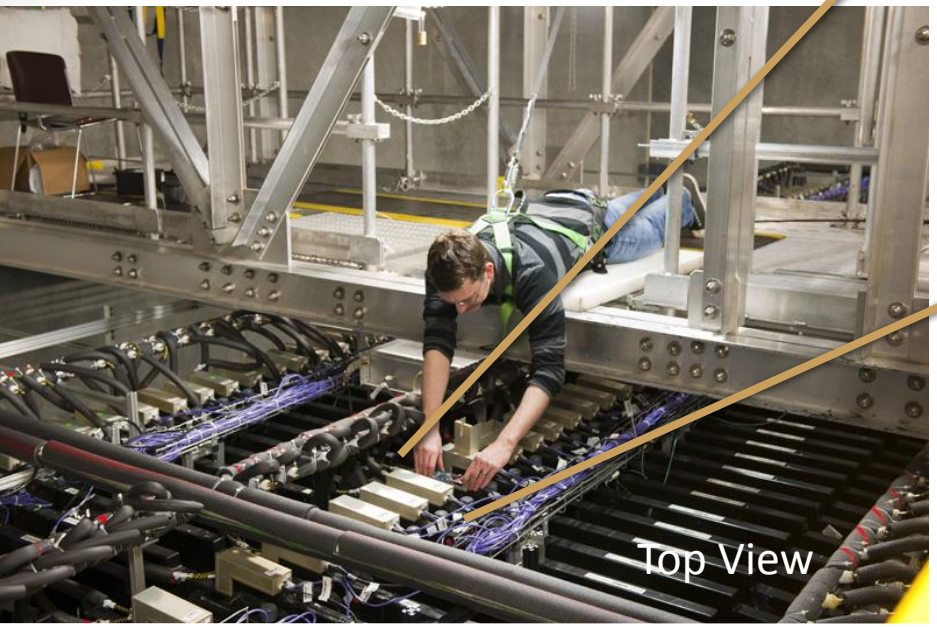


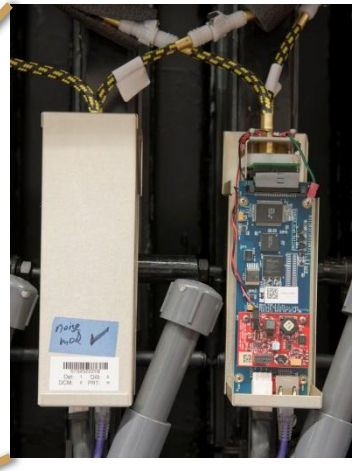
Prototype detector

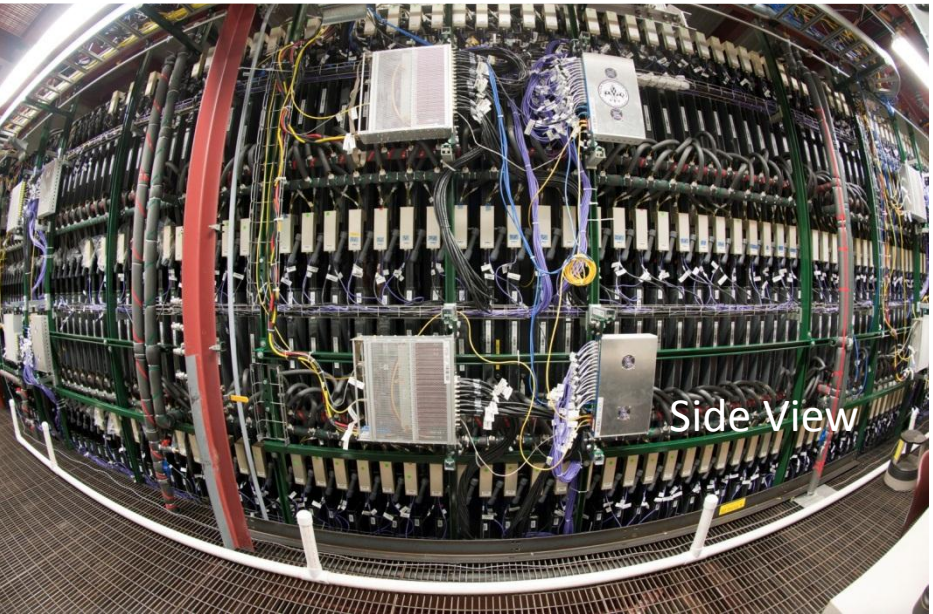
- Main goals are:
  - Test detector design and prepare for far detector production.
  - Develop DAQ system on custom design hardware
  - Tune calibration procedures.

- NDOS collects data from NuMI and BNB beams
  - Show electron neutrino selection and $e\backslash\pi^0$ separation.
  - Verify cosmic background suppression.
  - Study nuclear hadronization models and multinucleon production.
  - Quasi-elastic cross section at 2 GeV.

Lessons Learned

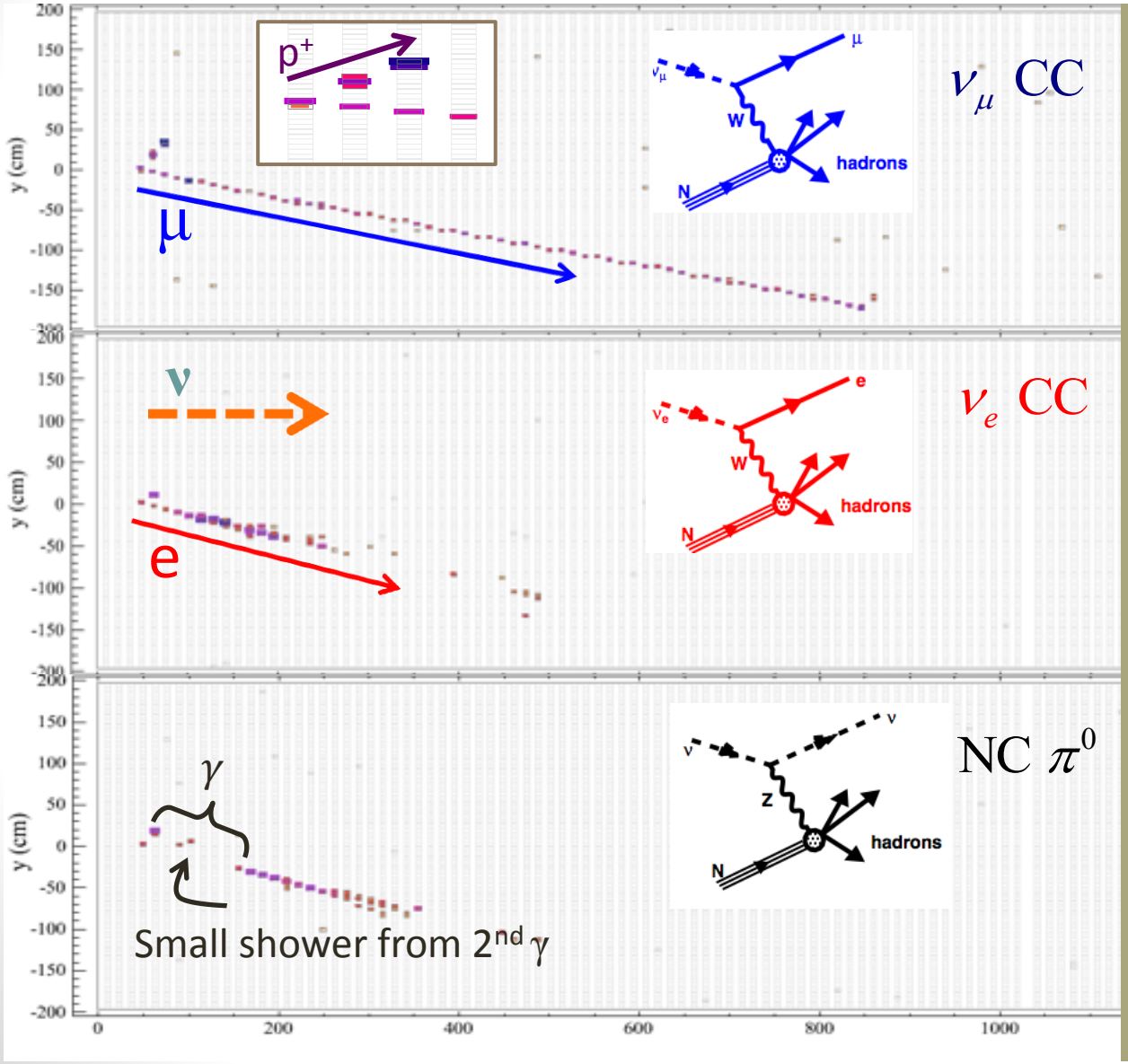






- Redesign of module manifolds to improve its structural integrity
- A few new quality assurance stages in the module production and installation.
- New installation procedures.
- Identification and fixing of DAQ performance issues.
- APDs and electronic redesign.

MC Events in NOvA



V_μ Charged-current

Long well-defined muon track, proton is a short track with large energy deposition at the track end.

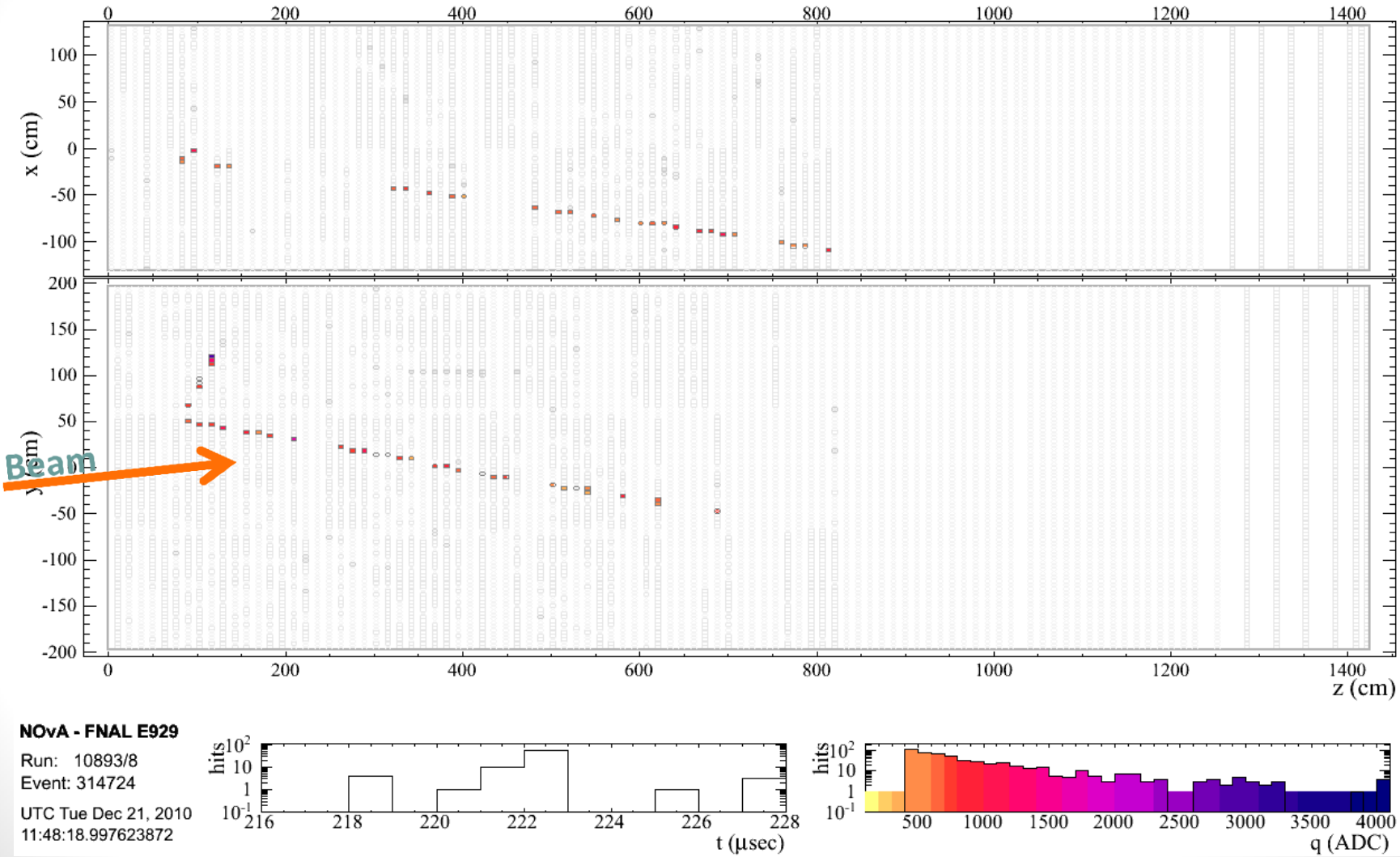
V_e Charged –current

Single shower with characteristic e-m shower development.

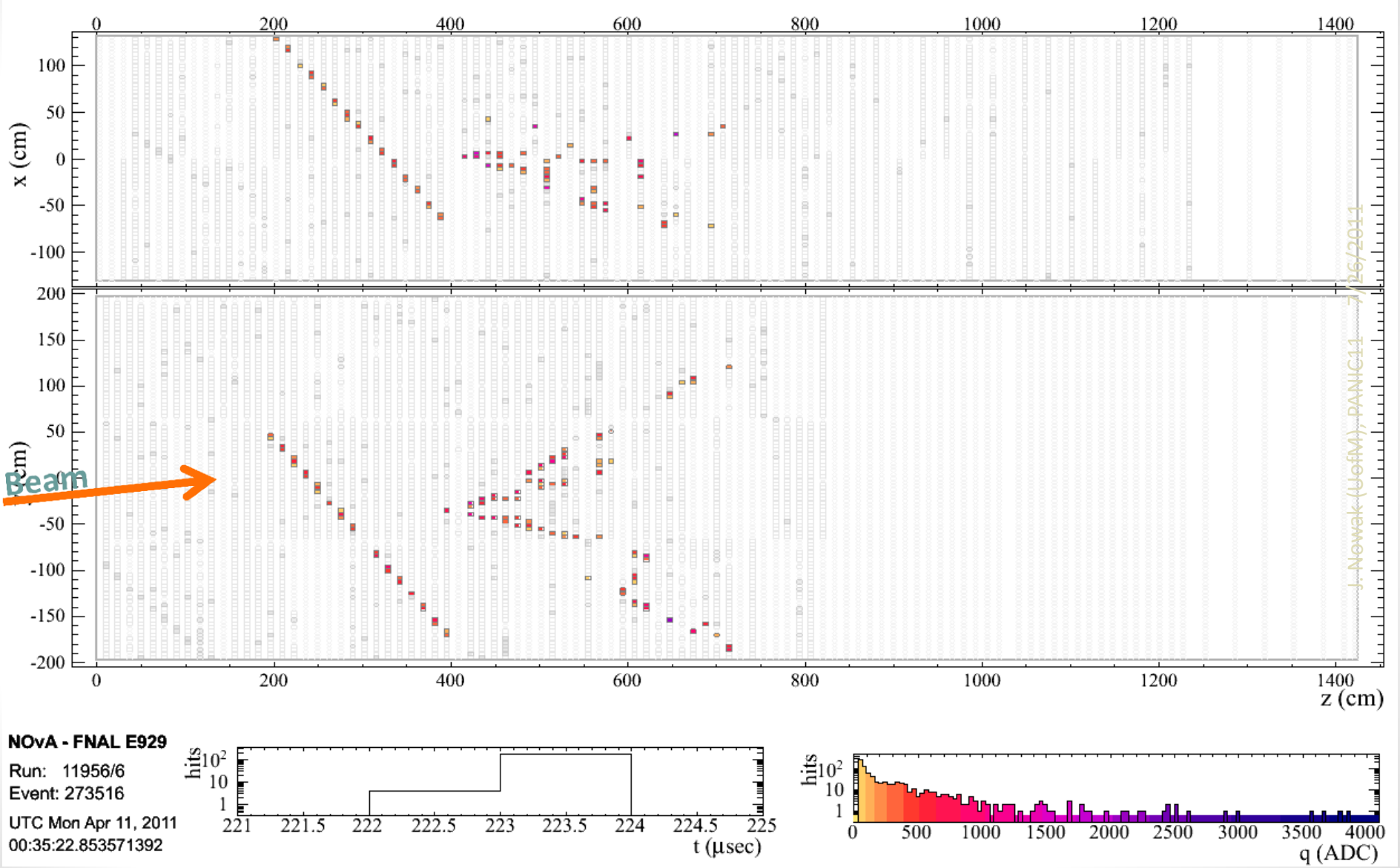
NC with π^0 in final state

Possible gaps near event vertex, multiple displaced e-m showers.

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)
q (ADC)

Neutrinos


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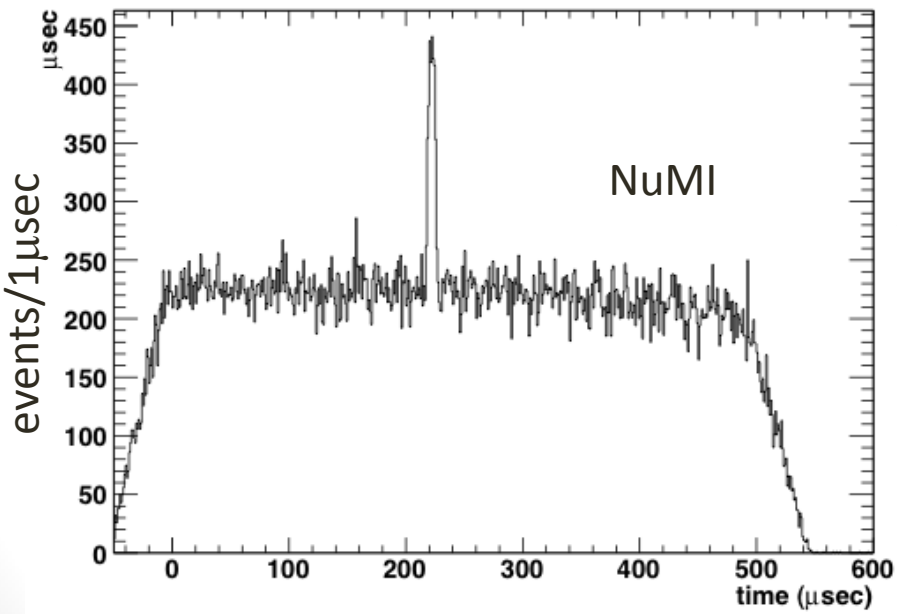
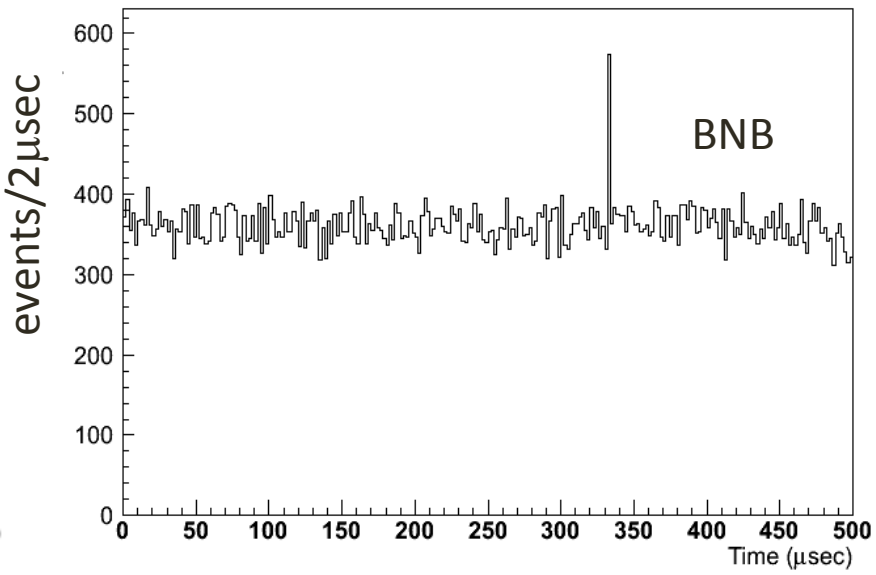
Finding Neutrinos

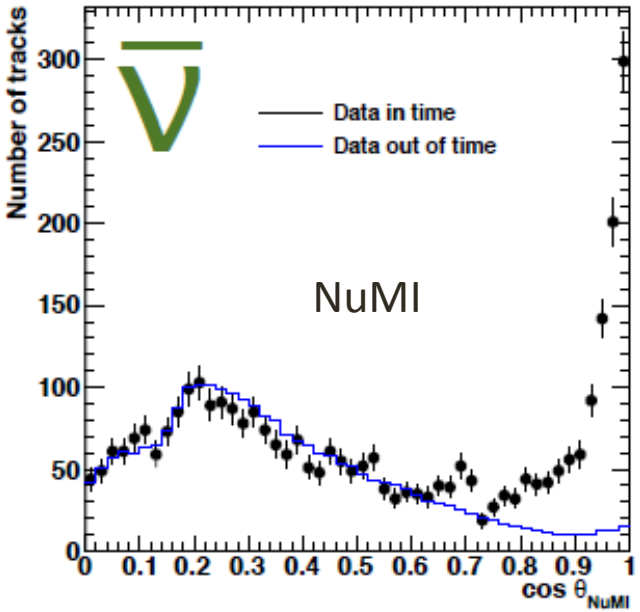
- Neutrino candidates selection cuts bring clear peak of beam events.
- 110 mrad off NuMI axis
- NDOS nearly on Booster axis, but detector rotated wrt axis





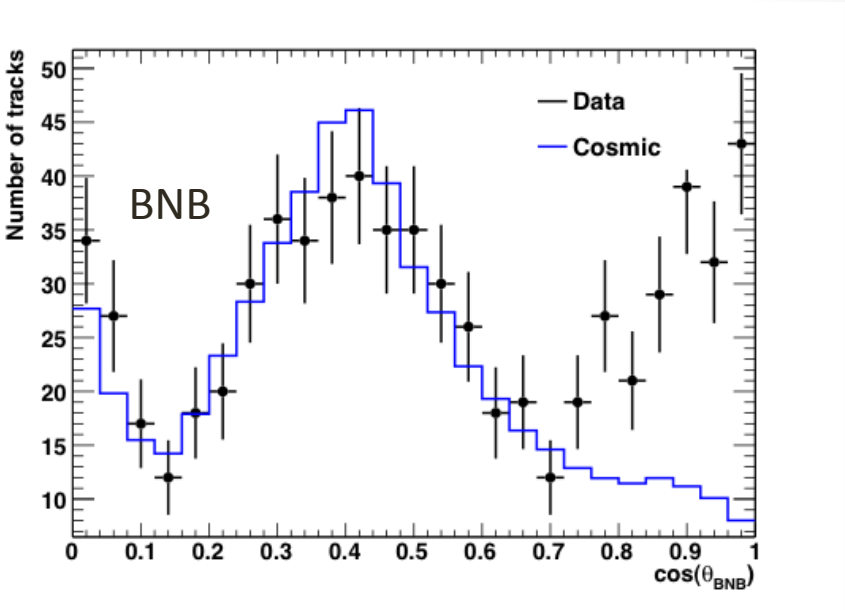
Neutrino candidates

- 110 mrad off NuMI axis



	PoT	NuMI	Cosmic Bg
Neutrino	5.6e18	253	39
Antineutrino	8.4e19	1001	69

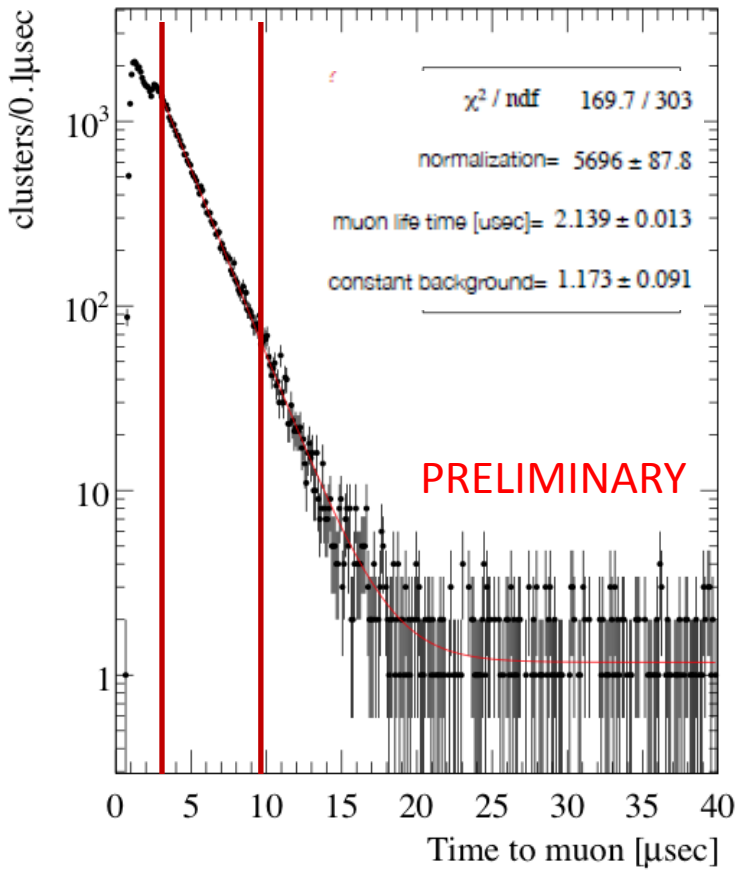
- NDOS nearly on Booster axis, but detector rotated wrt axis

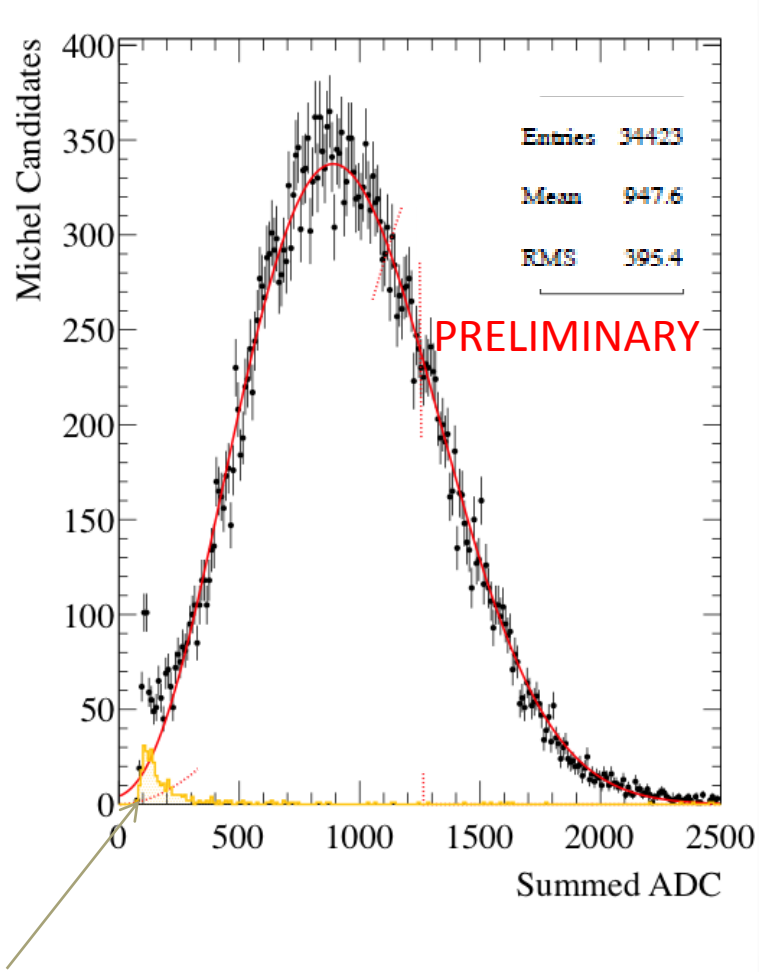


	PoT	BNB	Cosmic Bg
Antineutrino	3e19	222	92

Michel Electrons

- Use Michel electrons for electro-magnetic energy calibration





- q>300 ADC counts
- t>40 μsec into the spill
- cluster to be within 30 cm of muon end point

Random coincidences. These are clusters that are matched to muons recorded 20 seconds prior to event.

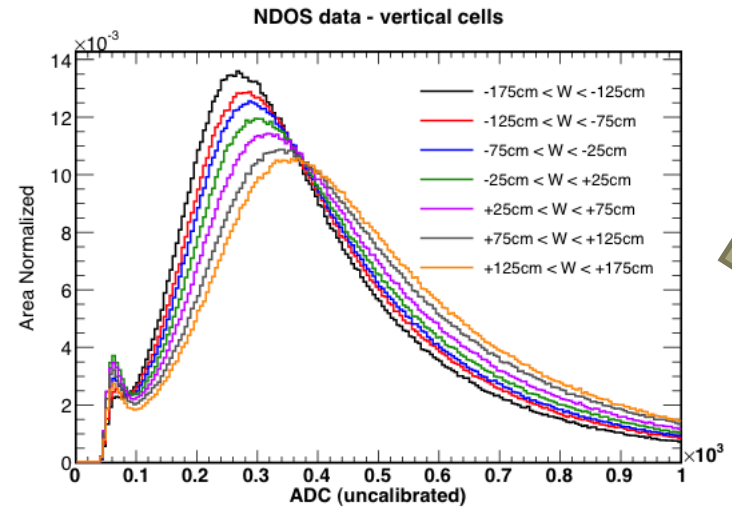
Summary

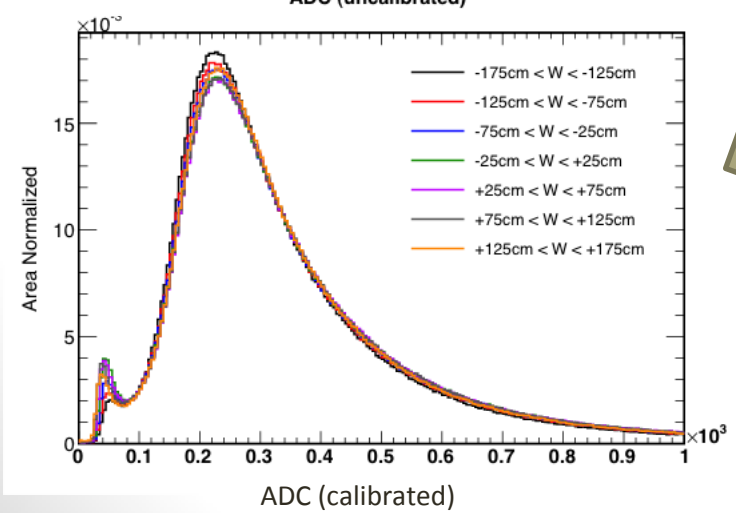
- NOvA is on track to make many important contributions to neutrino physics.
  - Measurement of θ_{13}
  - Determination of mass hierarchy
  - More precise measurements of Δm^2, $\sin^2(2\theta_{23})$
- Far detector construction coming soon.
- NuMI beam upgrade has started.
- Near detector on the surface taking neutrino data now.

BACKUP SLIDES

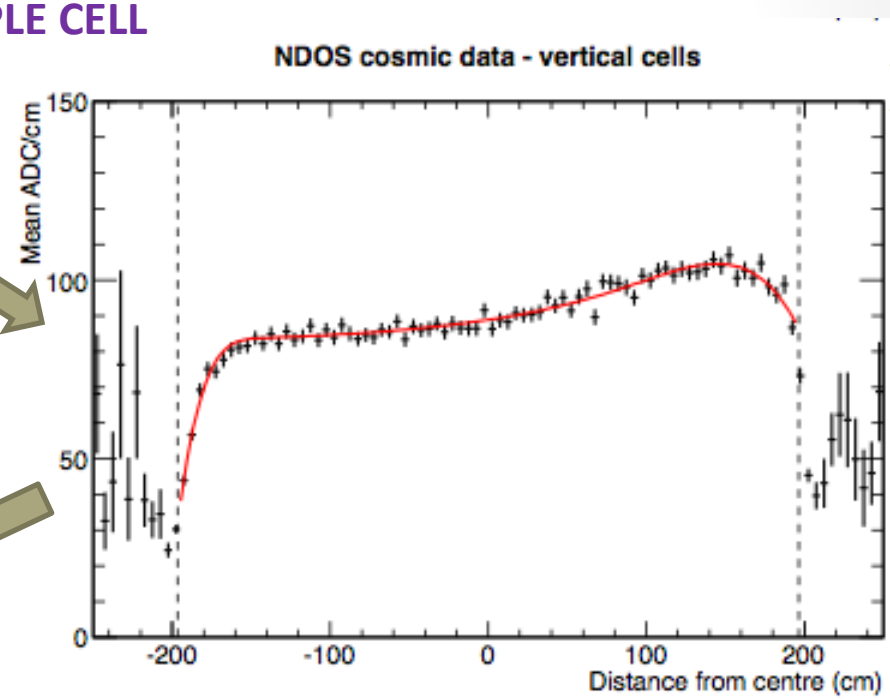
Calibration

- Cosmic muons provide intra-detector calibration source for every cell





EXAMPLE CELL



Neutrino Mixing

- **Massive neutrinos → mass eigenstates ≠ weak interaction eigenstate**
- Neutrino is produced in flavor α and can be detected in different flavor β
  - → depending on distance (L) travelled and neutrino energy (E) →L/E
  - → parameters: mixing angles (θ_{ij}) and mass differences $\Delta m^2_{ij}=m^2_i-m^2$

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

atmospheric and accelerator L/E~500km/GeV

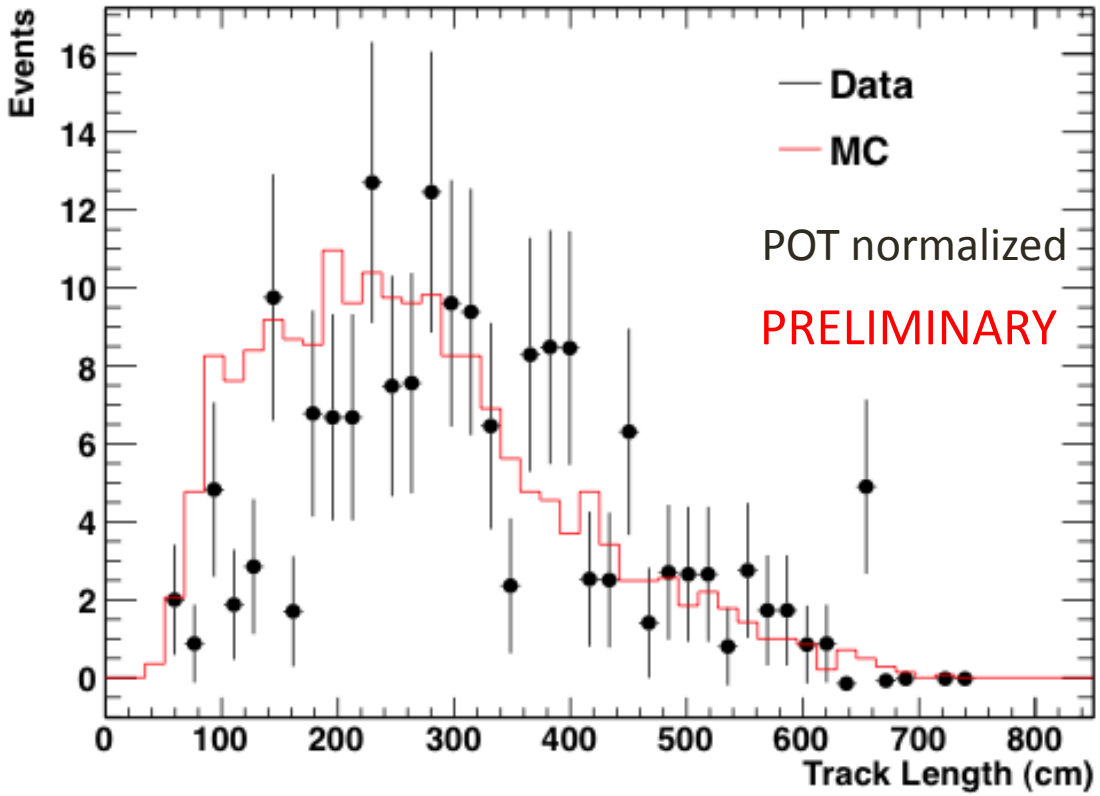
Indications of oscillation From MINOS and T2K

Reactor + Solar L/E~15,000 km/GeV

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

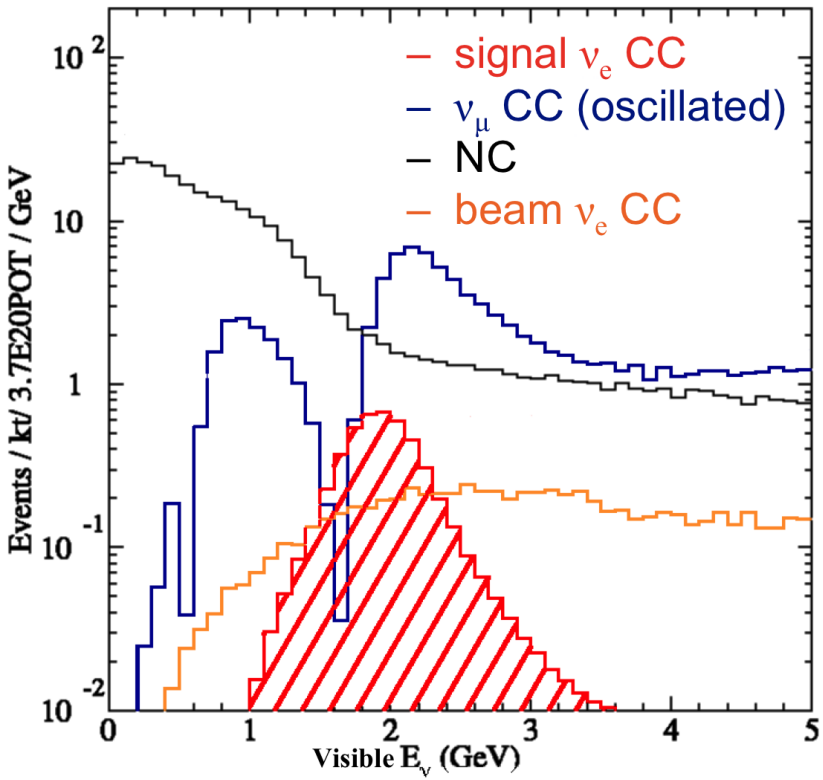
Comparisons to MC



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

	NuMI	Cosmic Bg	MC
Fiducial	1001	69	861
Fully contained	184	12	187

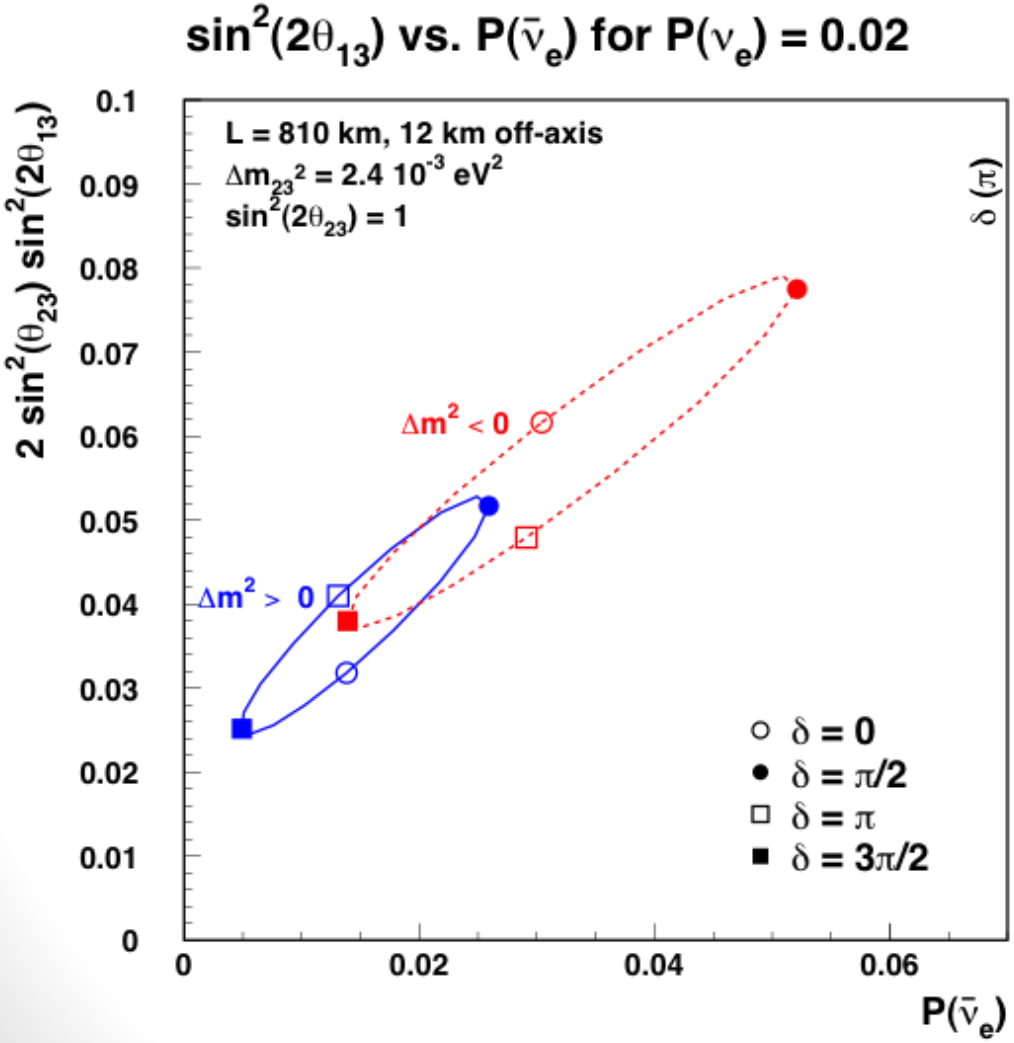
Case Study

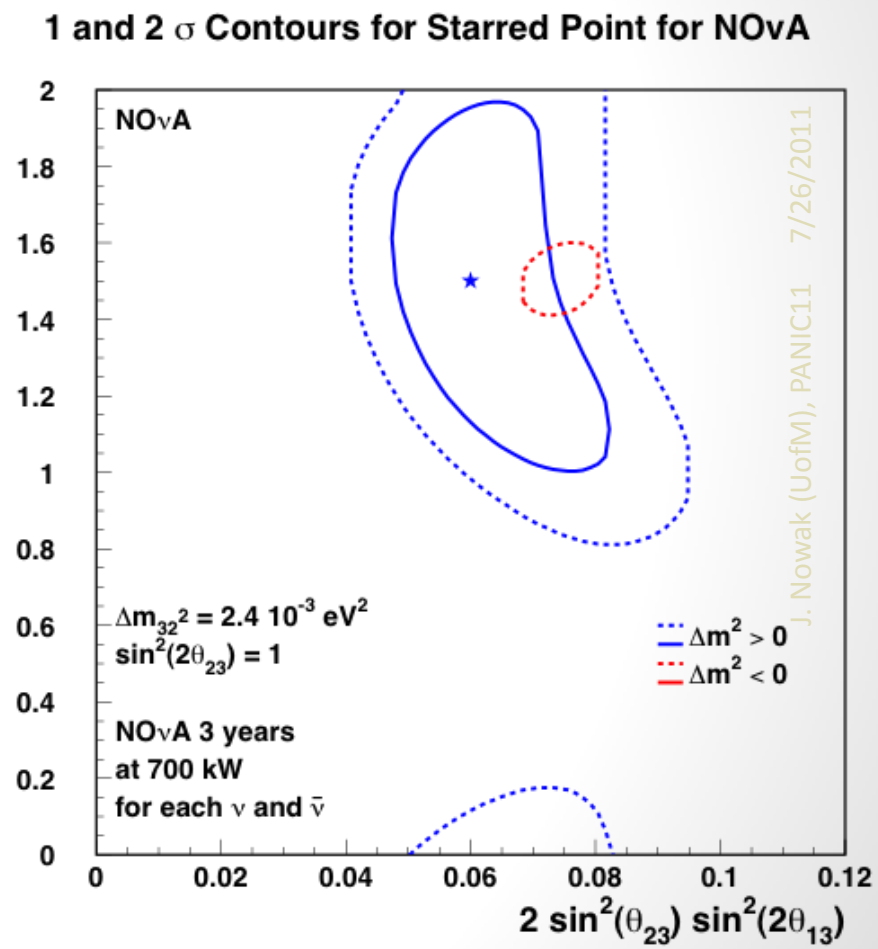


Interaction Type	Events in 3 years
ν_μ CC	2500
NC	2200
ν_e CC beam	120
ν_e CC signal	270

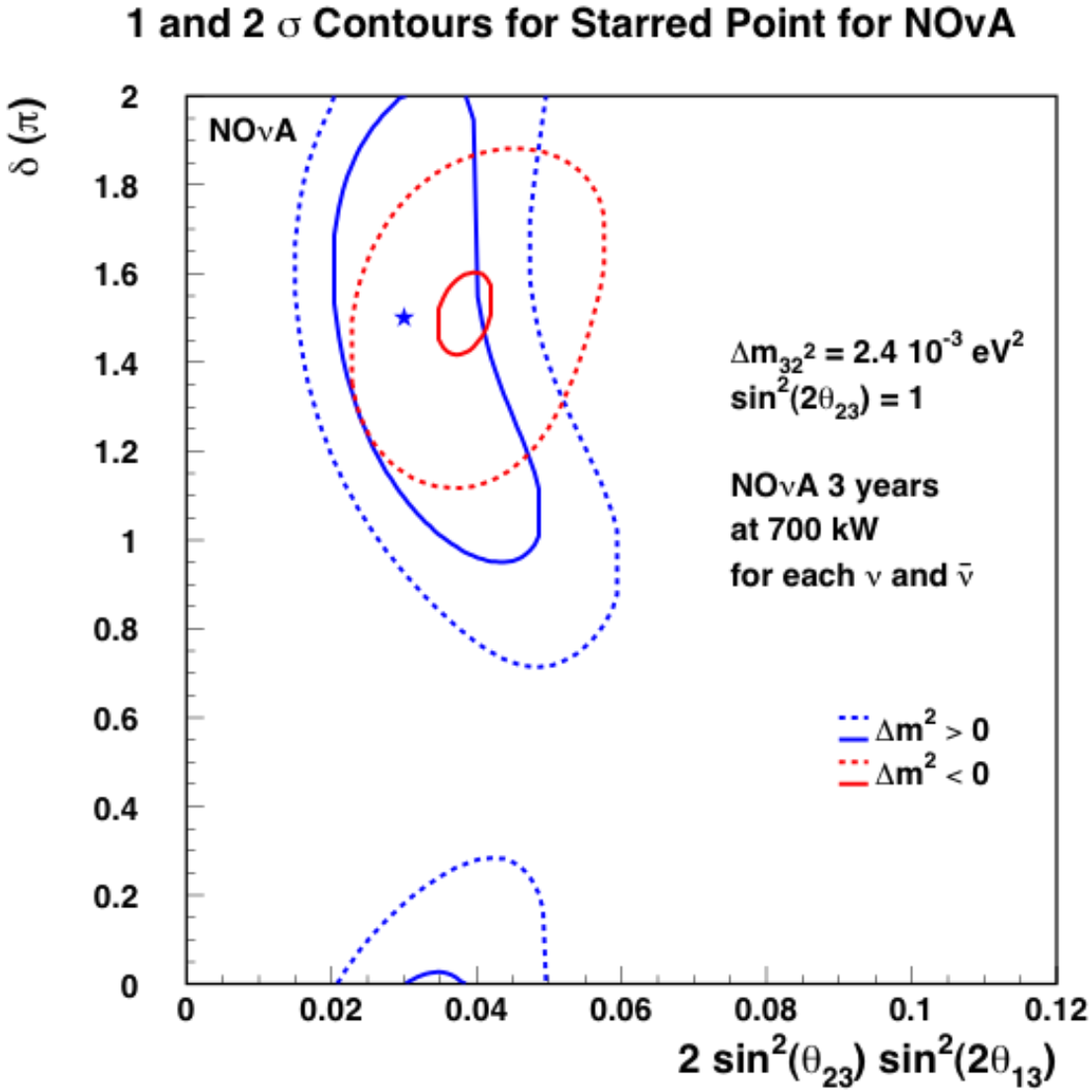
- Consider ν_e appearance at the CHOOZ limit:
  - Before cuts, signal is 4σ above background
  - Cuts on summed event pulse height, event length: 7σ
  - Sophisticated selection based on event topology: 18σ
  - Compare to ~4σ of MINOS analysis

Sensitivity to Hierarchy

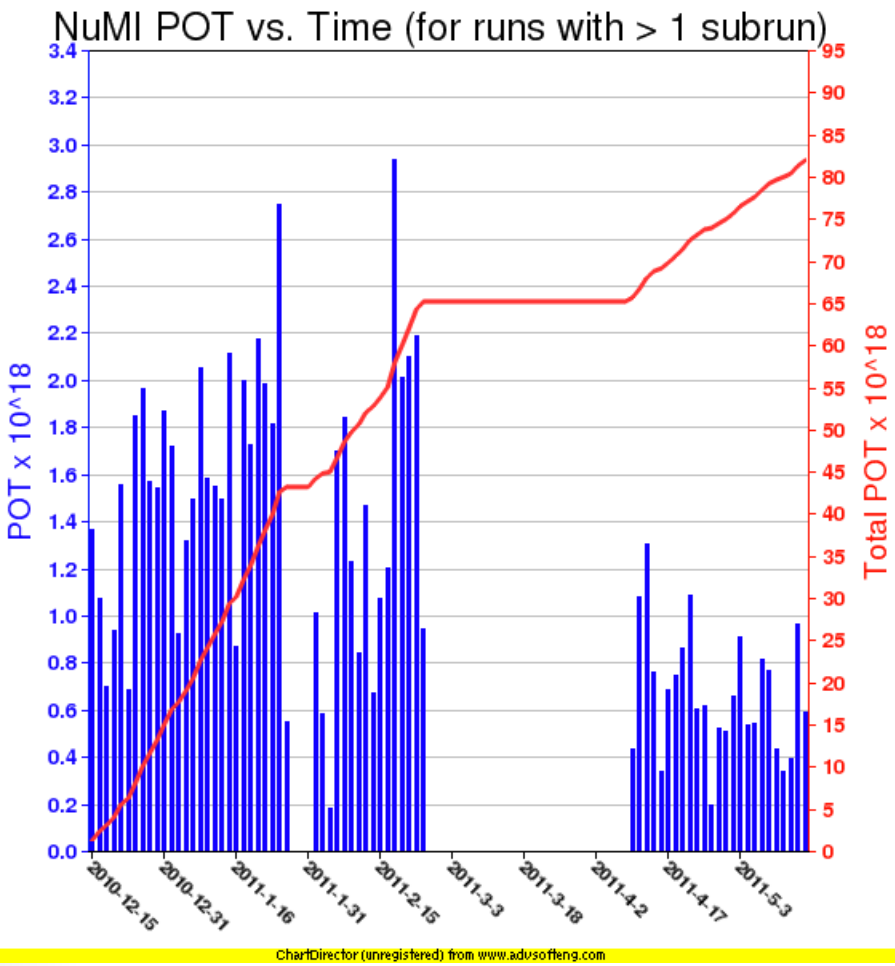


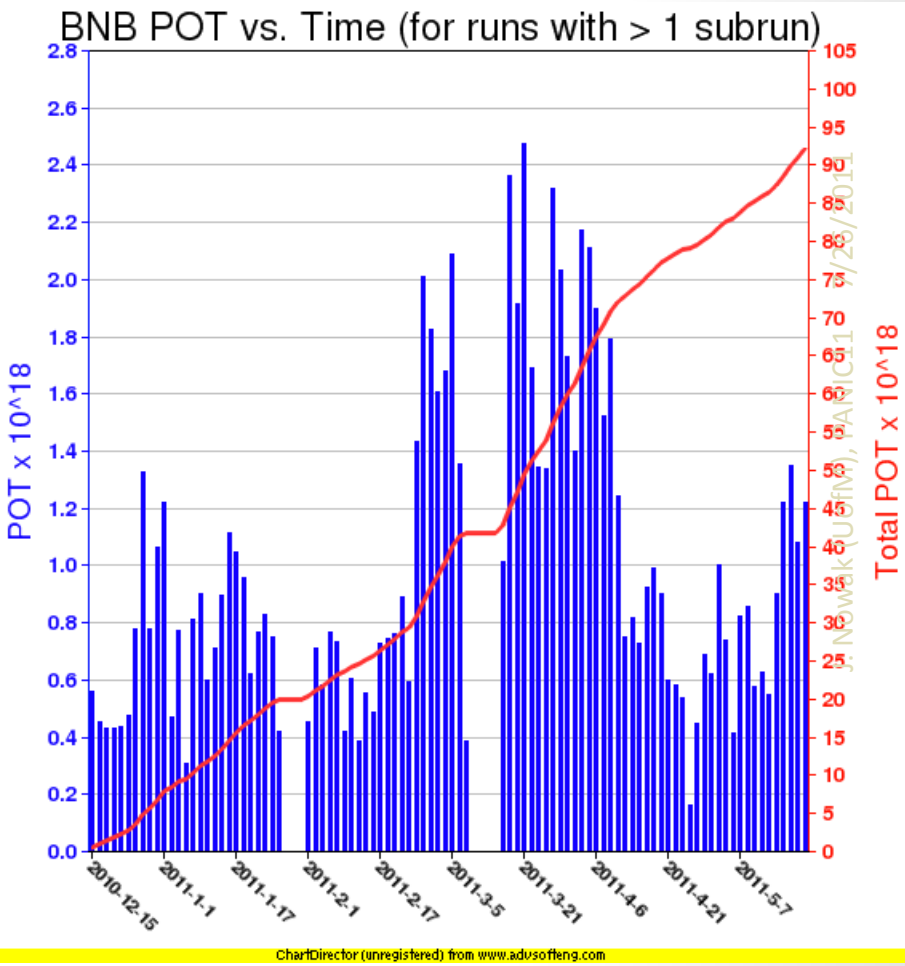


Example of Constraining CP

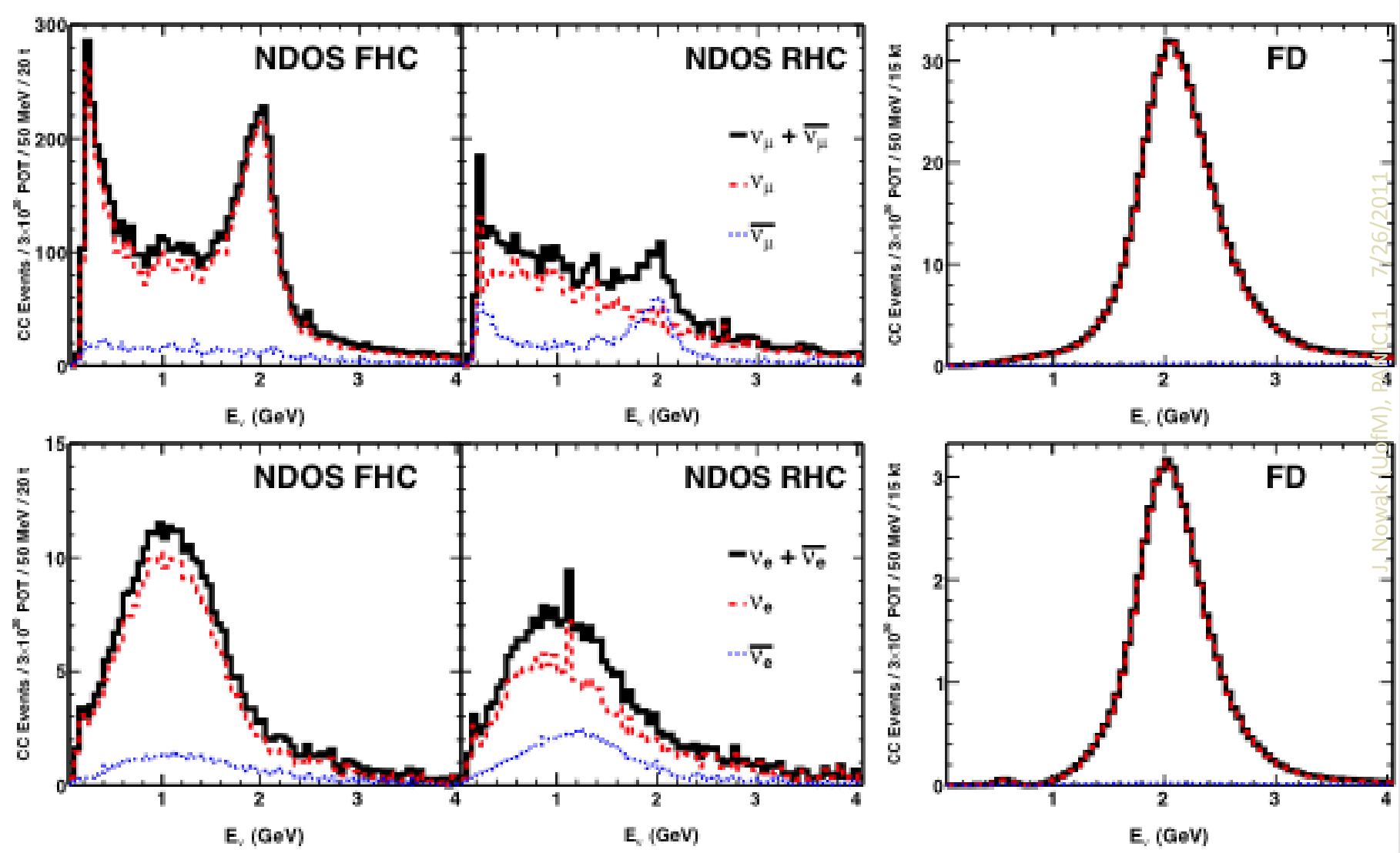


POT Accumulated

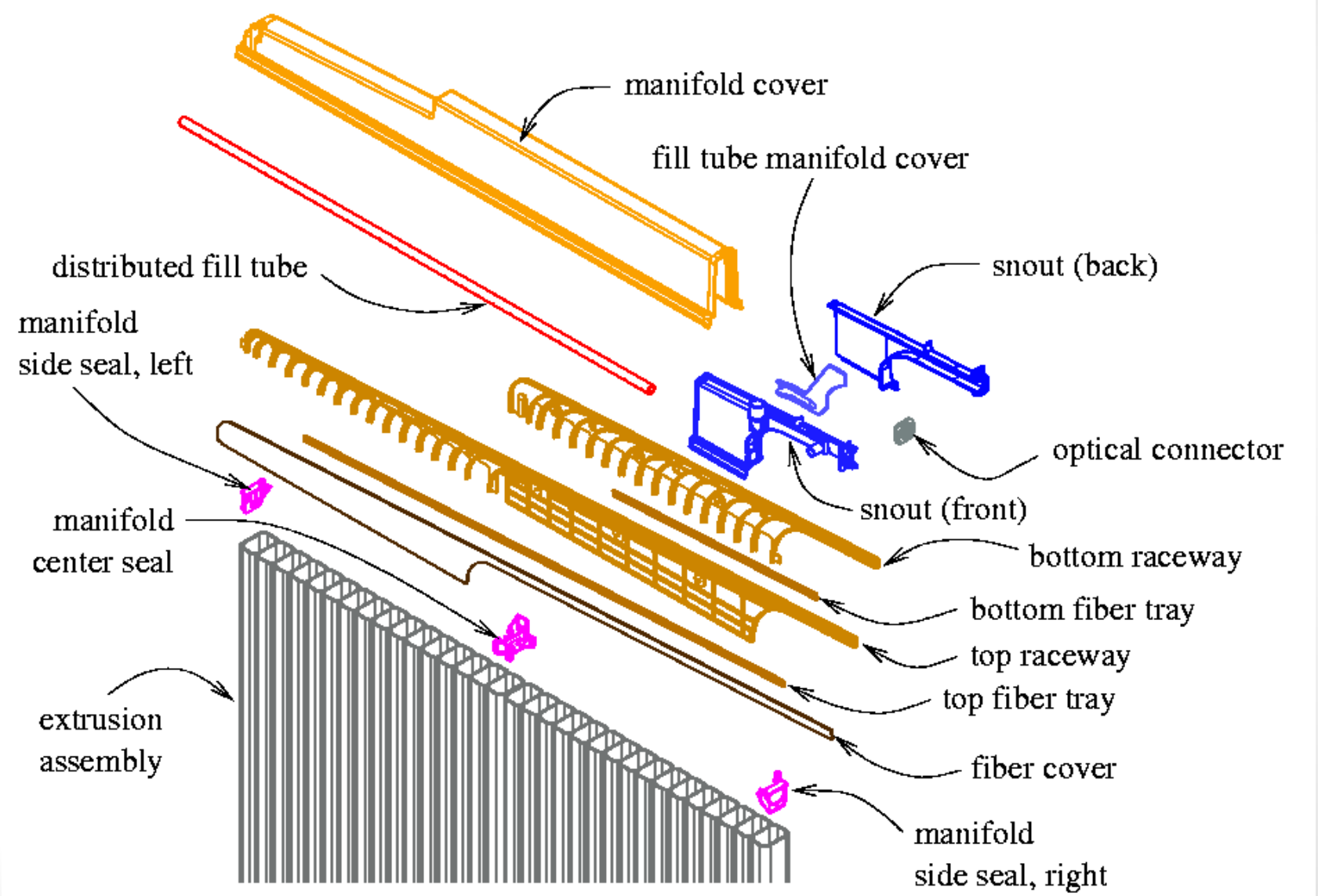




NDOS Energy Spectrum

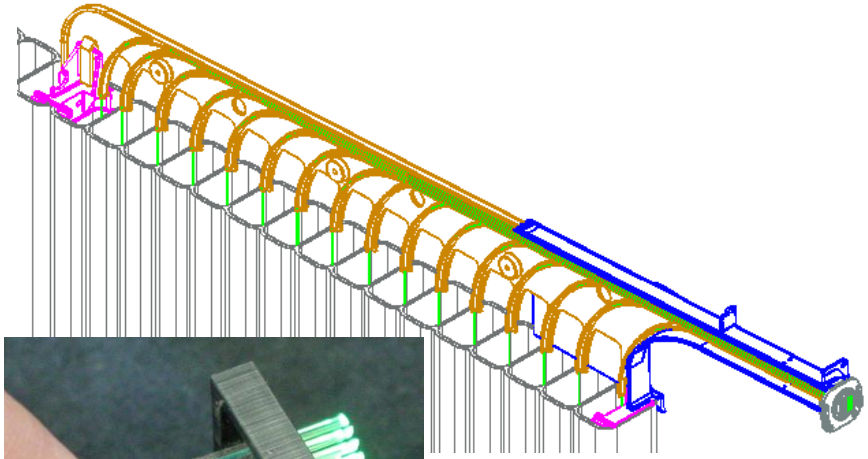


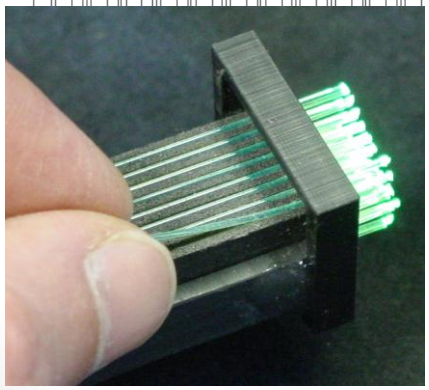
ND Manifold Architecture



Raceway Functionality

Face of optical connector





Threading fibers into opt conn

- Registers fibers in optical connector
- Guarantees acceptable bend radius
- Shields fibers from events in manifold
- Facilitates assembly

Module Construction Process