First Data from the NOvA Experiment

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for the NOvA Collaboration

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XXIV Workshop on Weak Interactions and Neutrinos

XXIV Workshop on Weak Interactions and Neutrinos
WIN 2013

Overview

- NOvA Experiment Introduction
- Physics Reach
- Current Status
- Summary

The NOvA Collaboration

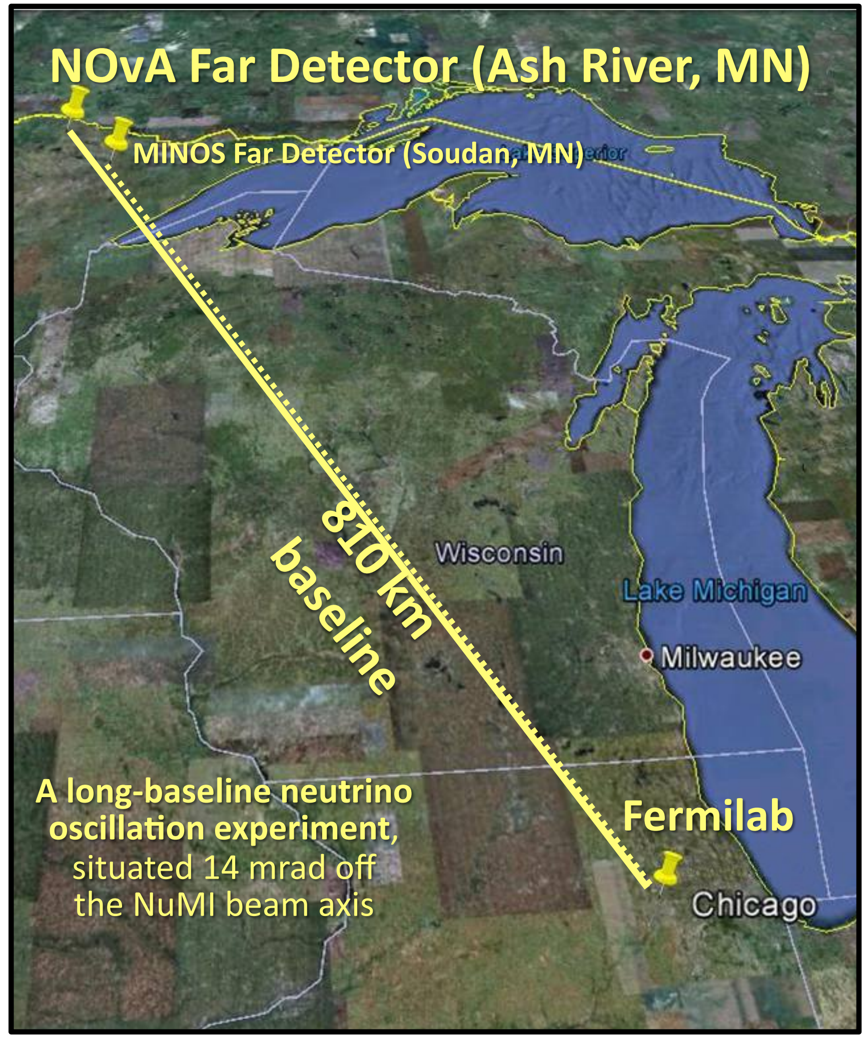
36 Institutions from 7 countries; 181 collaborators

Argonne National Laboratory · University of Athens · Banaras Hindu University · California Institute of Technology · Institute of Physics of the Academy of Sciences of the Czech Republic · Charles University, Prague · University of Cincinnati · Czech Technical University · University of Delhi · Fermilab · Federal Univ. of Goias · IndianInstitute of Technology, Guwahati · Harvard University · Indian Institute of Technology · University of Hyderabad · Indiana University · Iowa State University · University of Jammu · Lebedev Physical Institute · Michigan State University · University of Minnesota, Crookston · University of Minnesota, Duluth · University of Minnesota, Twin Cities · Institute for Nuclear Research, Moscow · Panjab University · University of South Carolina · Southern Methodist University · Stanford University · University of Sussex · University of Tennessee · University of Texas at Austin · Tufts University · University of Virginia · Wichita State University · Winona State University · College of William and Mary

The NOvA Experiment

NOvA

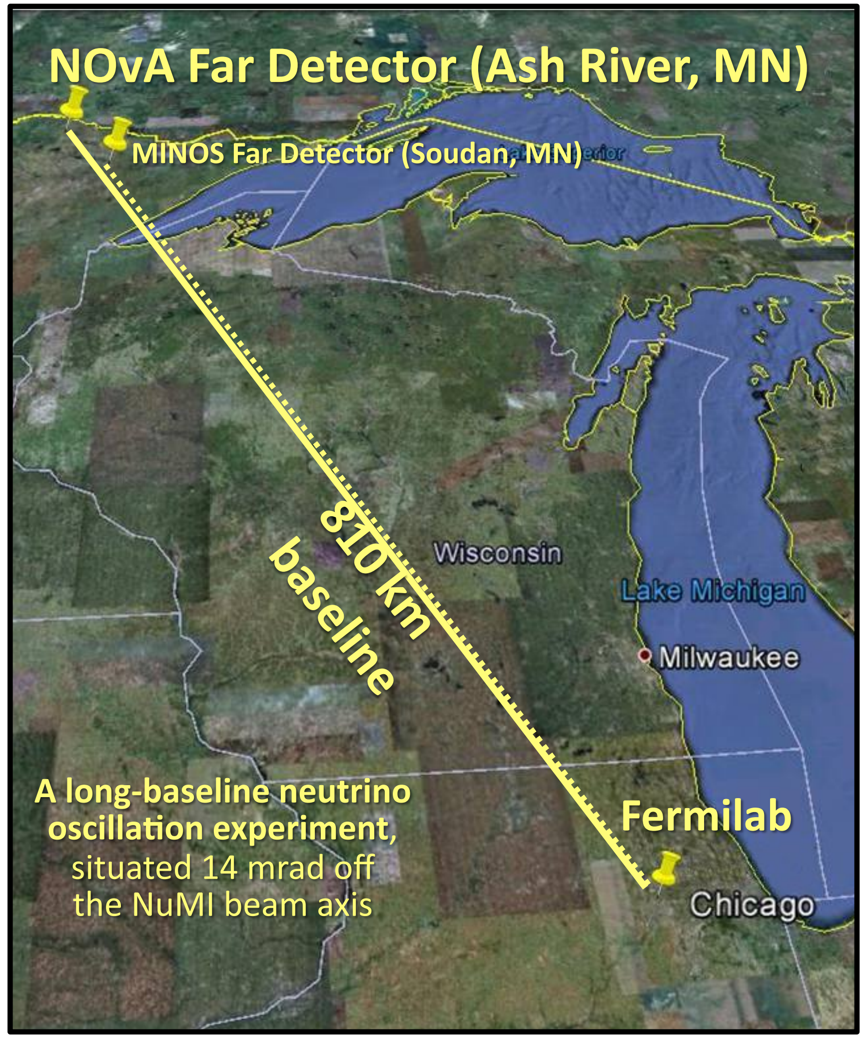
- NuMI (neutrinos from Main Injector) beamline (same as MINOS)
- Off-axis (14 mrad)
- ν_e Appearance



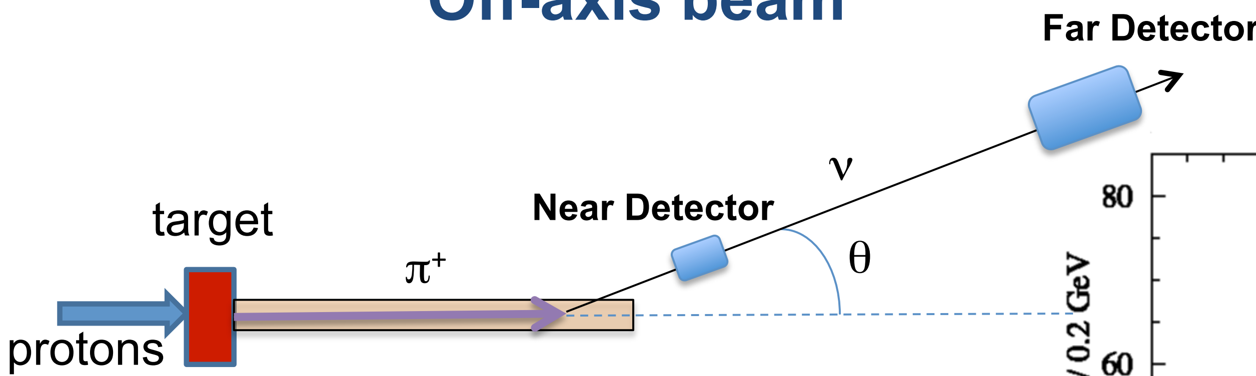
The NOvA Experiment

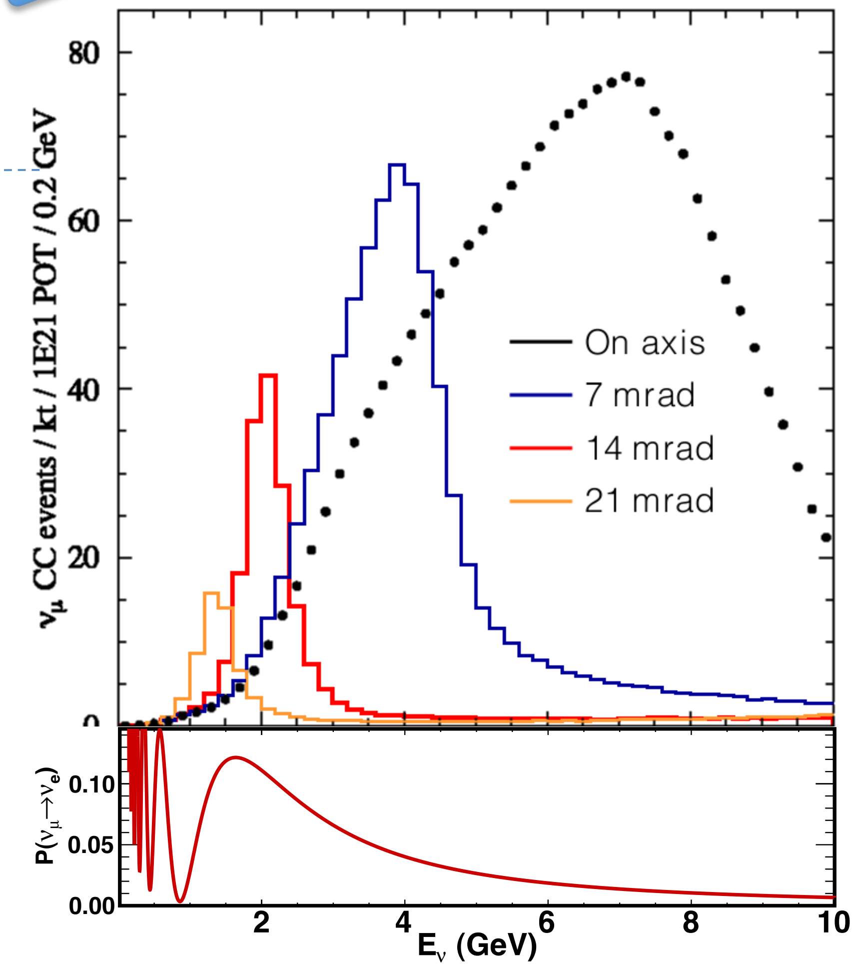
Goals:

- **Measure $\nu_\mu \rightarrow \nu_e$ oscillations.**
  - Measure θ_{13}
  - Determine the mass hierarchy
  - Constrain δ_{CP}
  - Determine the θ_{23} octant
- **Measure ν_μ disappearance.**
  - Precision measurement of $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$
- **Other physics**
  - Near Detector neutrino cross-sections
  - Sterile neutrinos
  - Supernova search
  - Monopole search
  - Dark matter searches



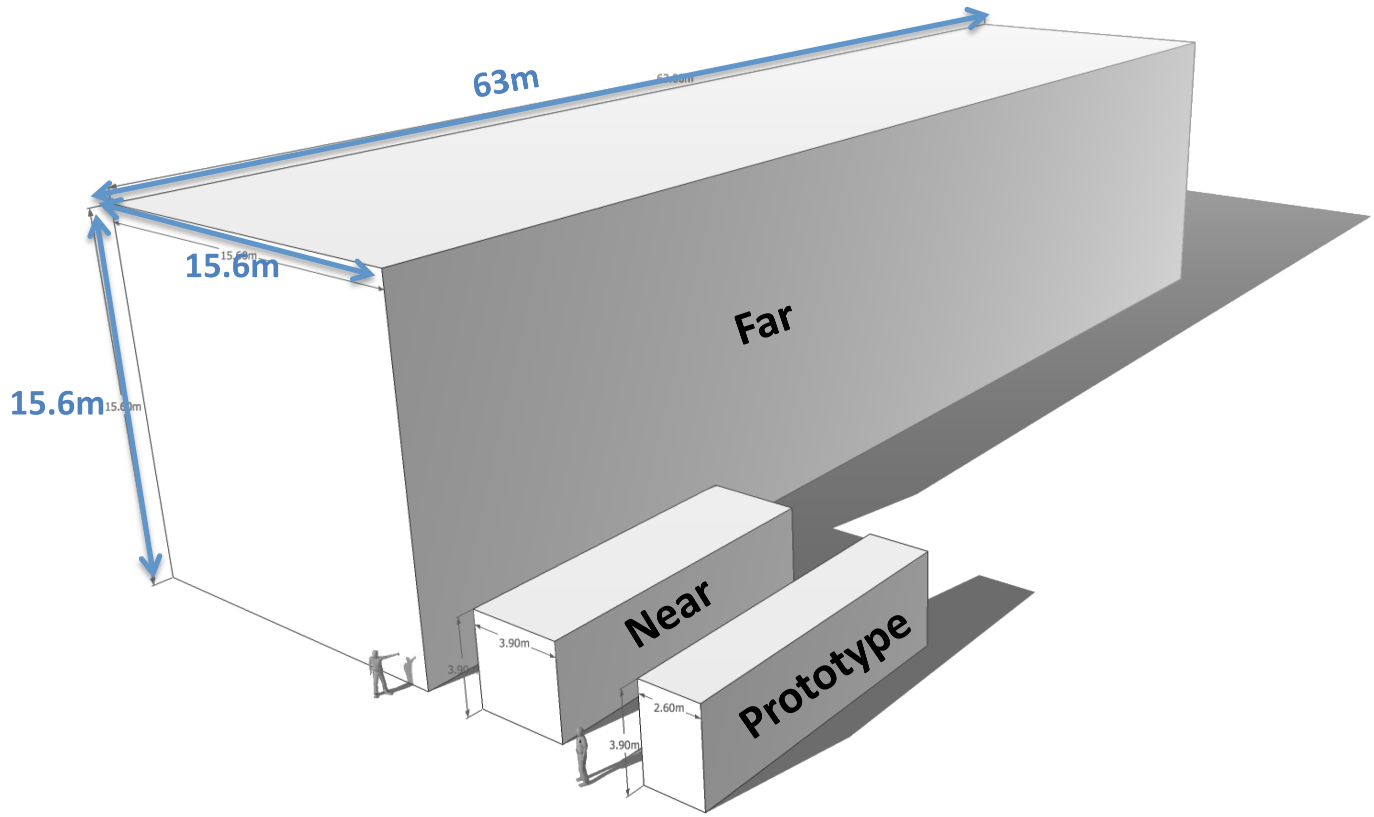
Off-axis beam





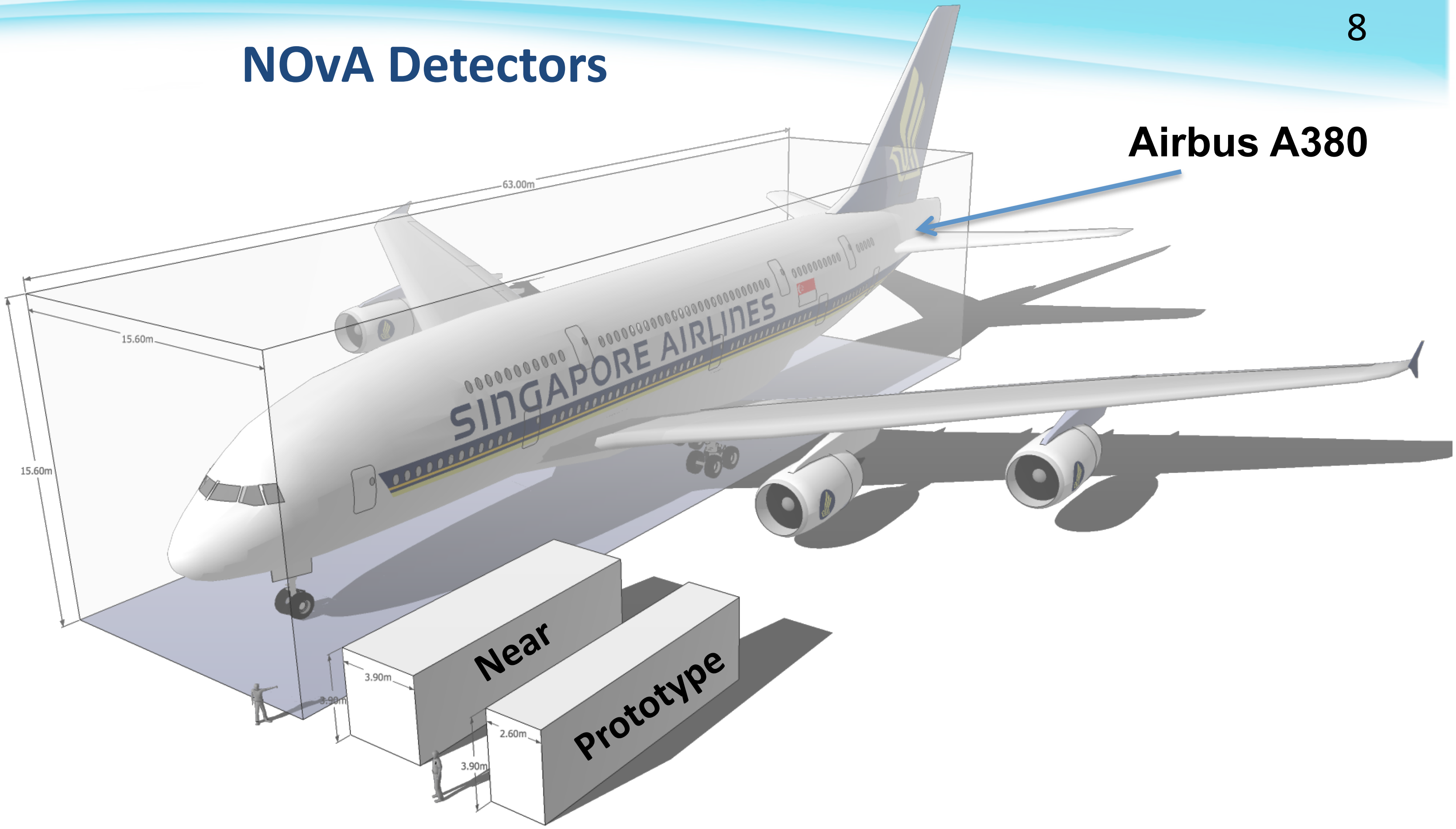
Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam.
Close to the first oscillation maximum at 810km.

NOvA Detectors



- **A Large 14 kton Far Detector**
- **A smaller functionally equivalent 0.3 kton Near Detector**

NOvA Detectors



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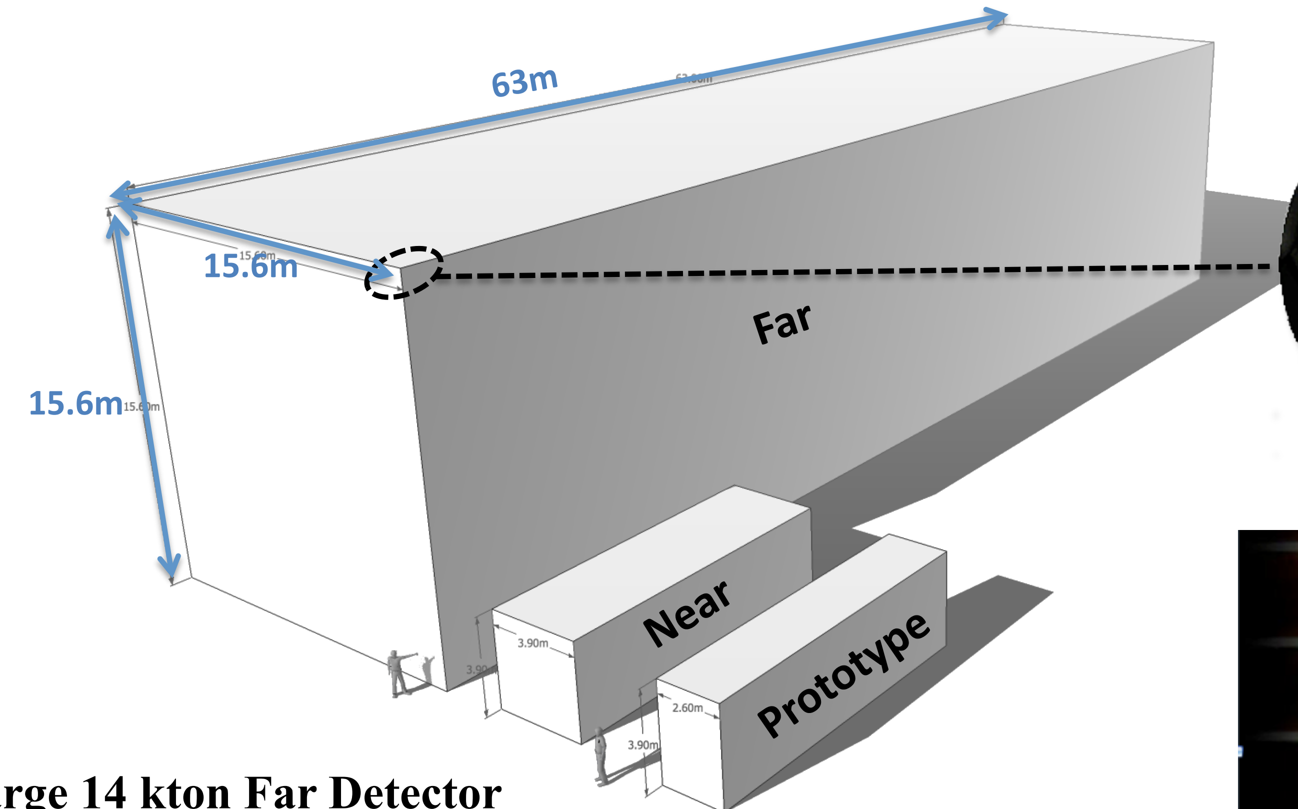
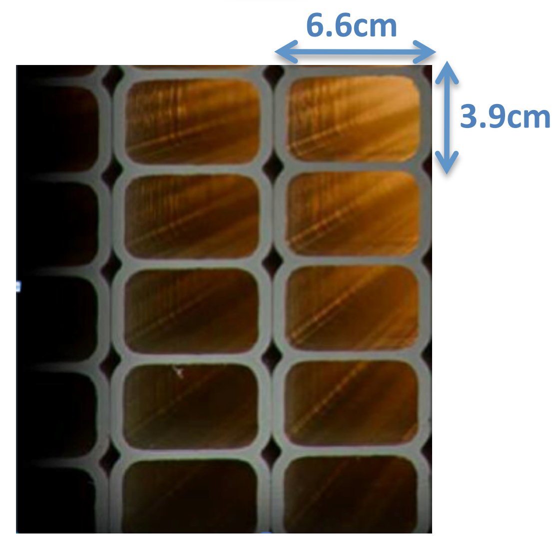
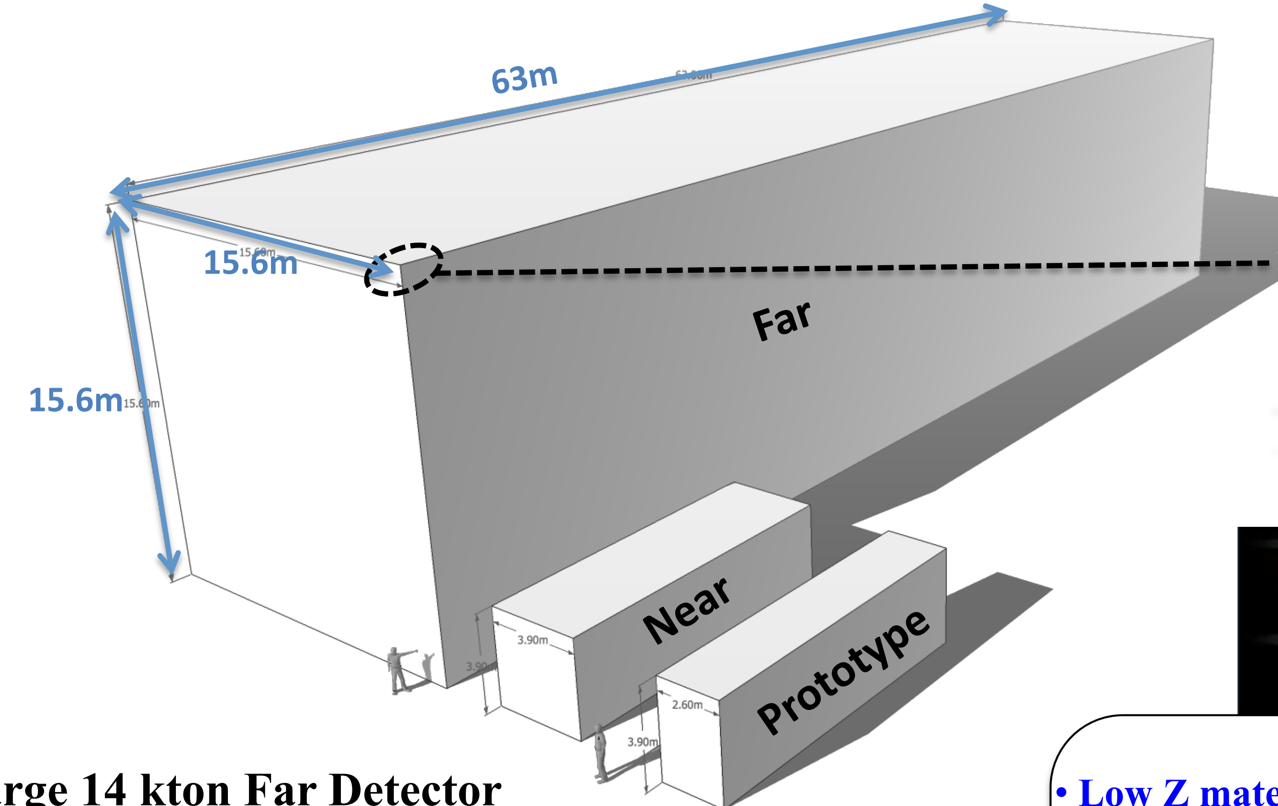
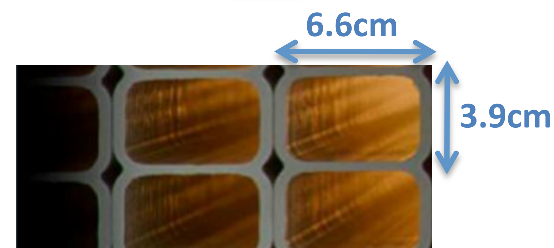




- **A Large 14 kton Far Detector**
- **A smaller functionally equivalent 0.3 kton Near Detector**
  - 6.6cm x 3.9cm x 15m cells made out of PVC. Total of 344,064 cells for Far Detector
  - Filled with liquid scintillator.
  - 896 alternating X/Y planes for Far Detector

NOvA Detectors





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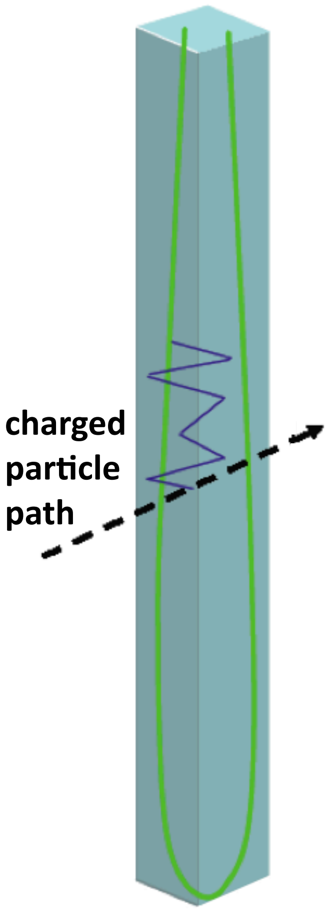
- **Low Z materials** (PVC and Scintillator)
  - X_0 = 40cm (6 planes)
  - R_M = 11cm (3 cells)
  - *(Great for e^- identification)*
- **63% Active Detector**

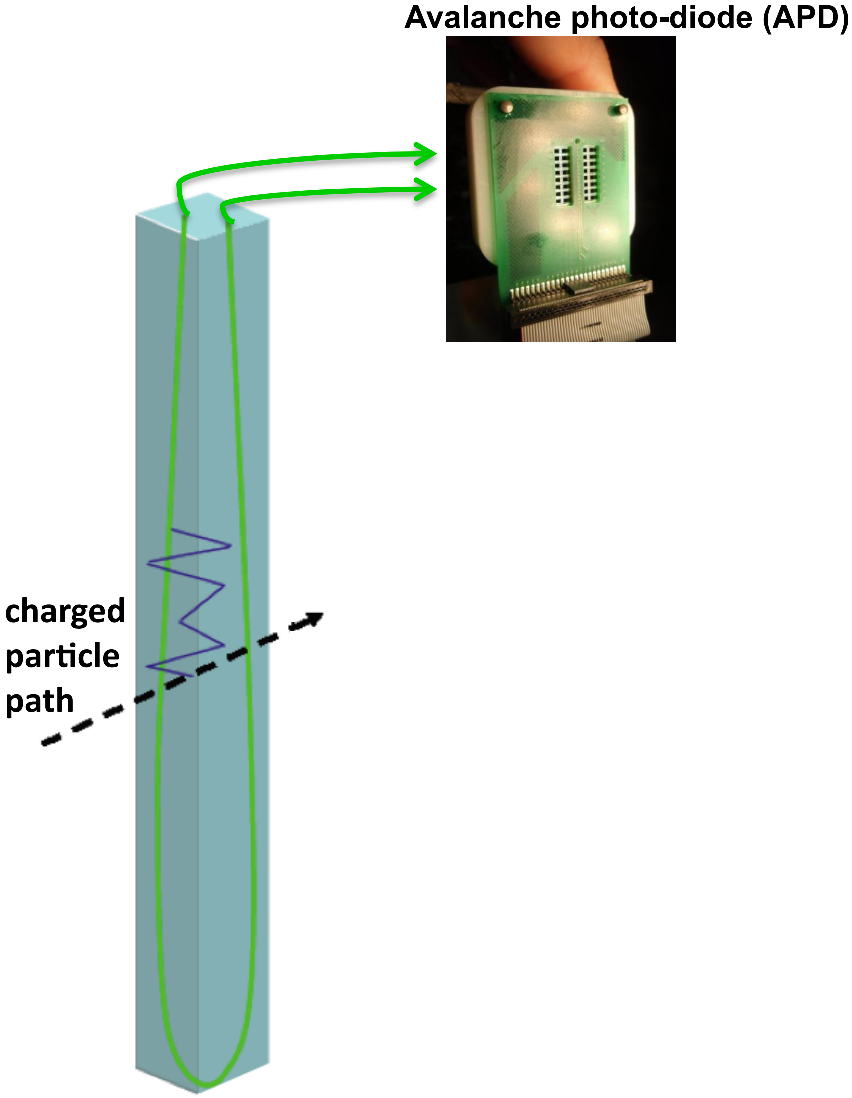
Detector Technology and Electronics

NOvA Cell



•**Wave length shifting fiber** collects light, shifts the light from violet to blue-green

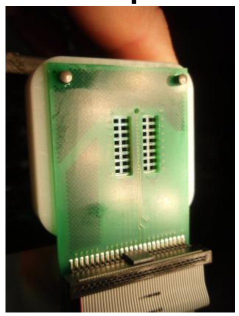
Detector Technology and Electronics

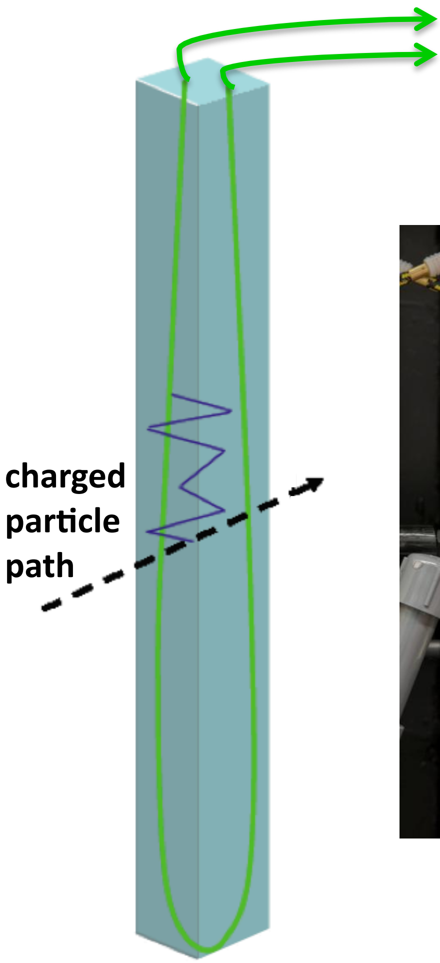


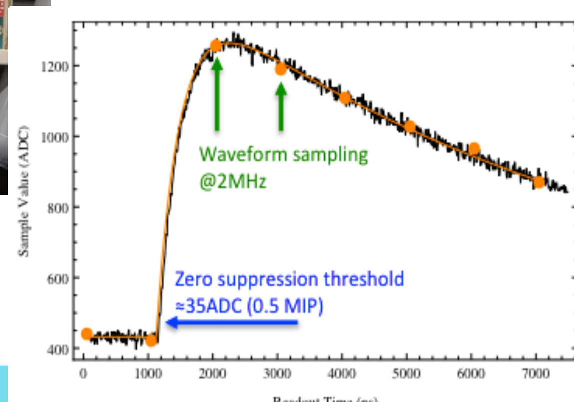
- **Wave length shifting fiber** collects light, shifts the light from violet to blue-green
- **APDs**
  - Costs about $10 per channel
  - Gain of 100
  - Quantum efficiency ~80%.
- The **cooling system** actively cool the APDs to -15^{o}C in order to decrease the electronic noise.
- The **gas drying system** ensures that the APDs remain dry all the time.

Detector Technology and Electronics

Avalanche photo-diode (APD)







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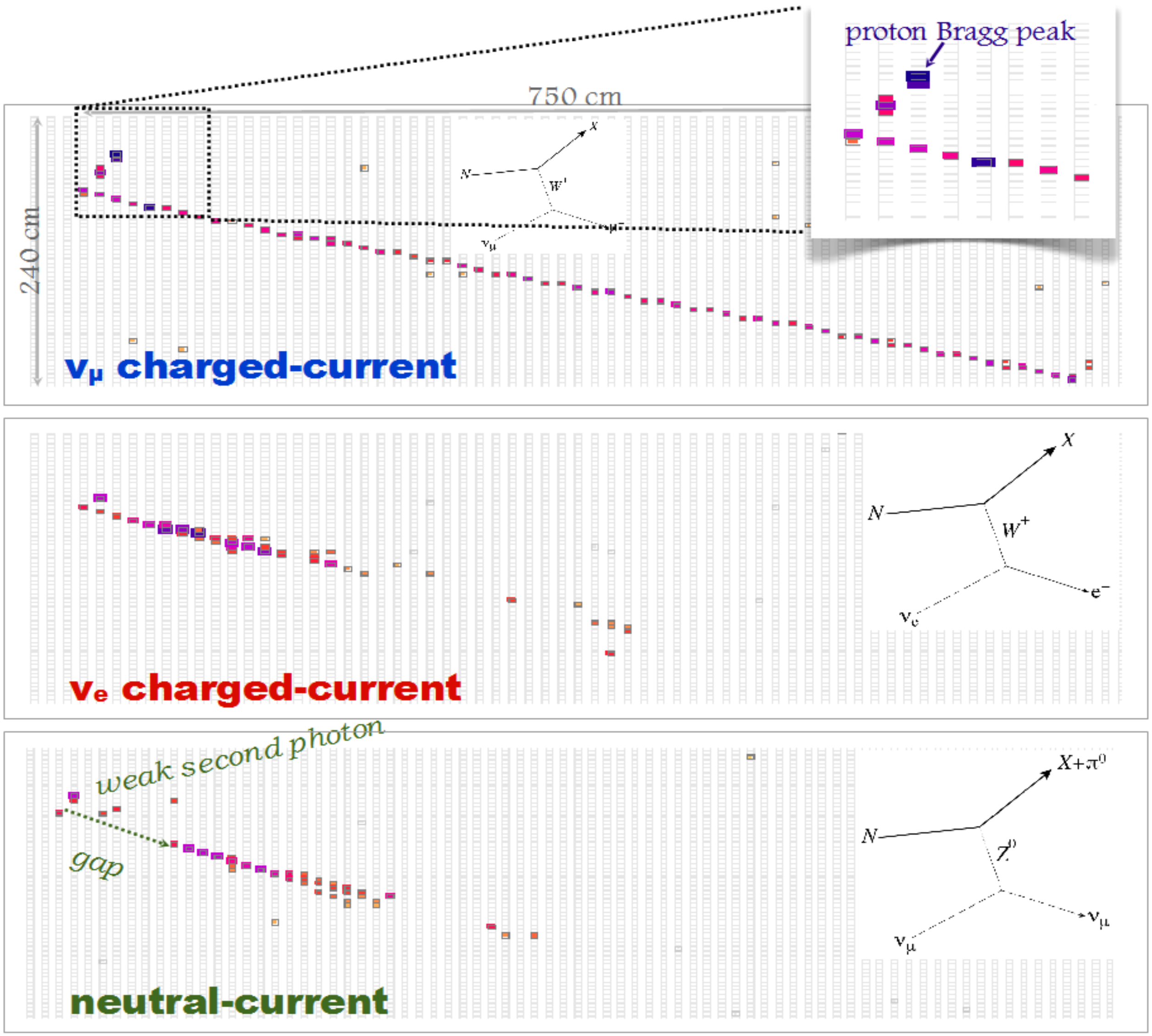
• The **gas drying system** ensures that the APDs remain dry all the time.

•**Front End Boards :**
- ❑ Low-noise ASIC amplifier to maximize the sensitivity to small signals.
- ❑ Analog-to-digital converter samples each pixel with a frequency of 2 MHz (8 MHz at Near Detector)
- ❑ APD temperature control

Simulated Neutrino Interactions



ν_μ charged-current

- long, well-defined muon track
- short proton track with large energy deposition at end

ν_e charged-current

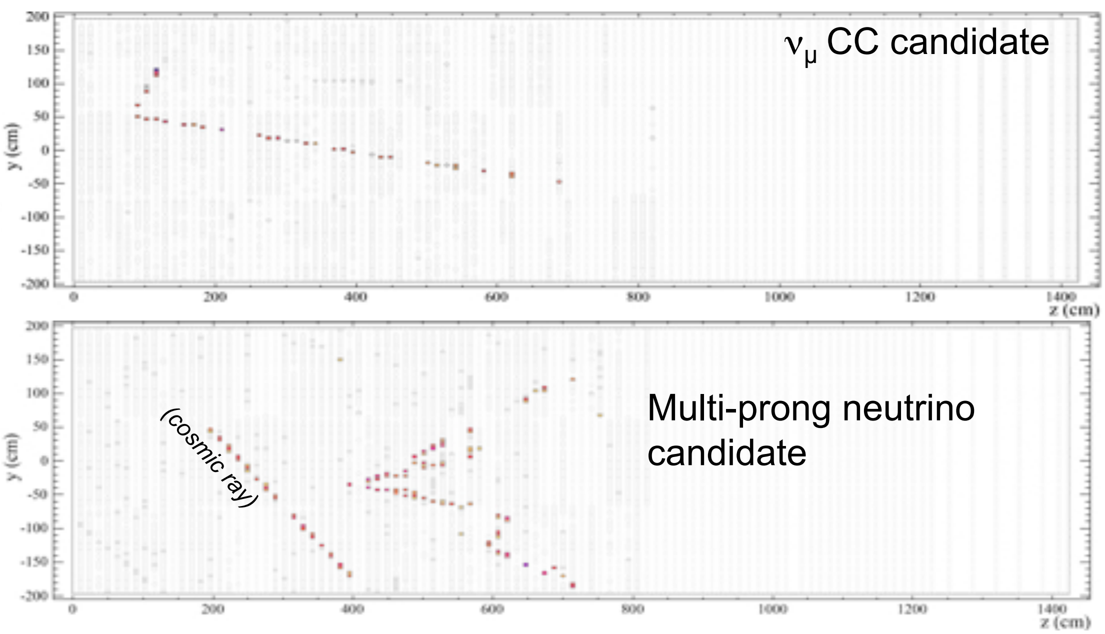
- single EM shower
- characteristic EM shower development

Neutral-current with π^0 final state

- multiple displaced EM showers
- possible gaps near event vertex

Prototype Near Detector on Surface

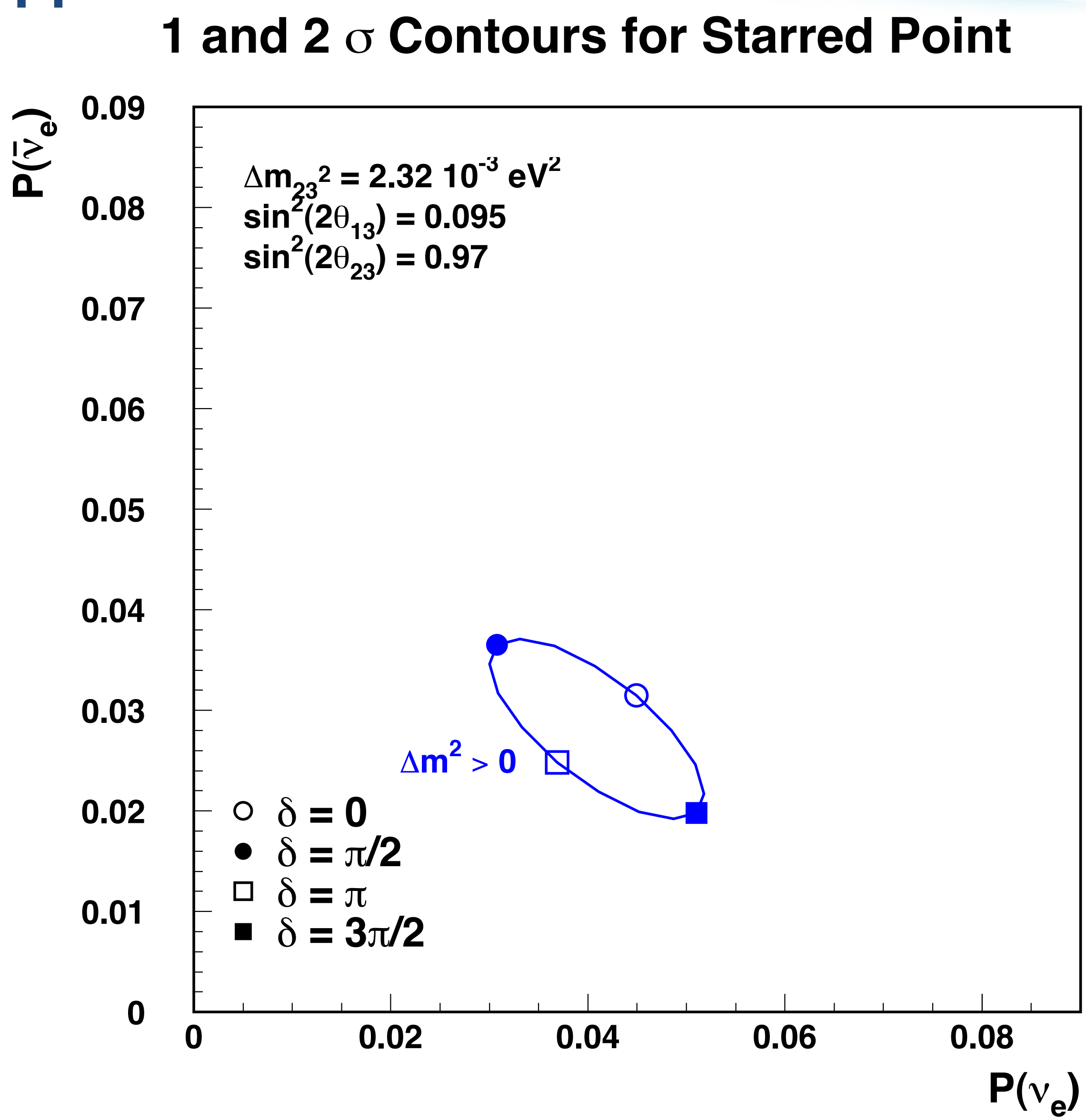
- Tested detector design, installation procedures, electronics, DAQ.
- Collected beam data from two neutrino beamlines from December 2010 to April 30th 2012.
- Analyzed Data, performed calibrations.



Physics Reach

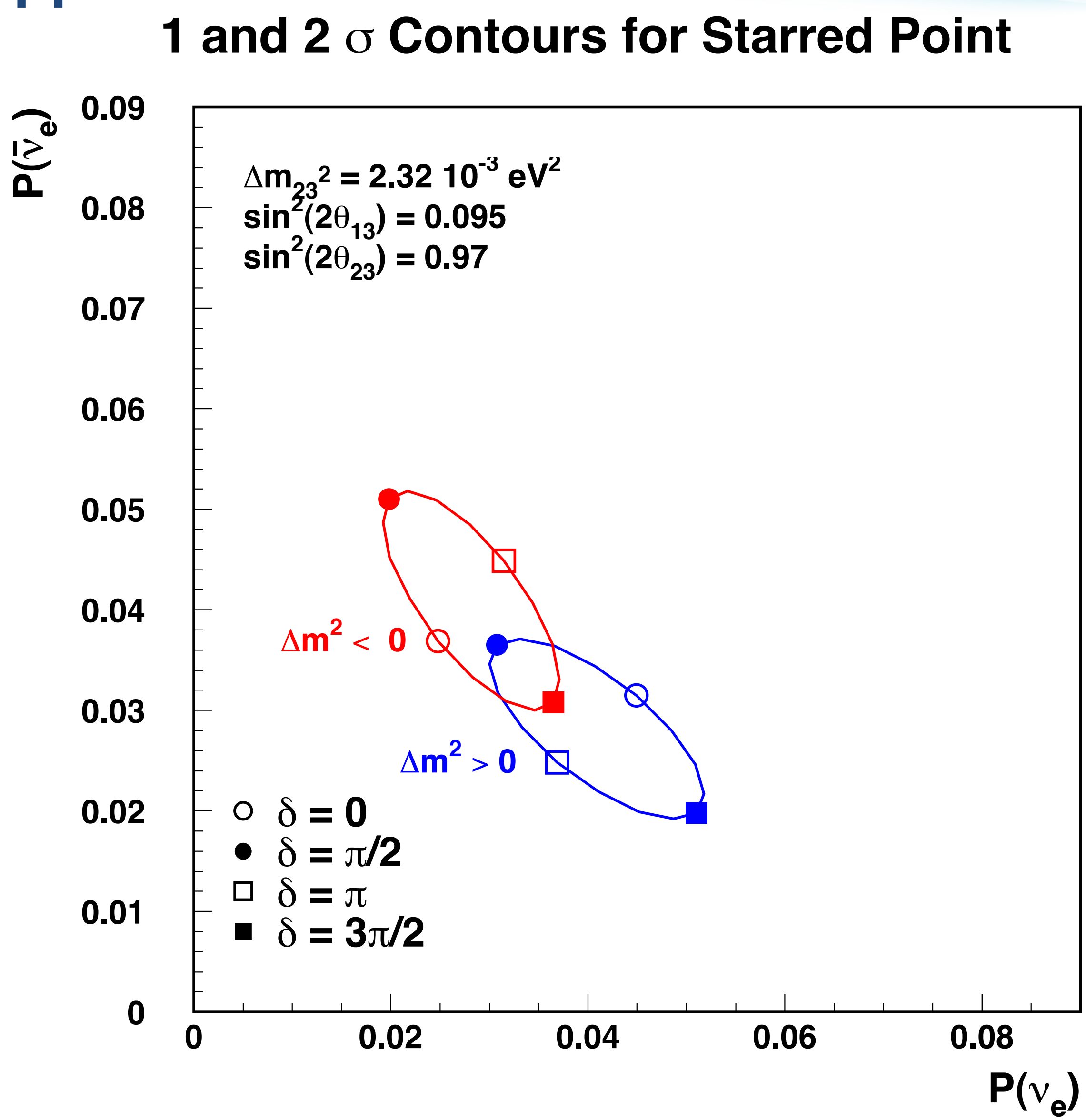
$\overset{(-)}{\nu}_e$ Appearance

Probability of oscillations for both ν_m and ν_m as a function of δ.



$\overset{(-)}{\nu}_e$ Appearance

Inverse mass hierarchy gives different values for the probabilities.

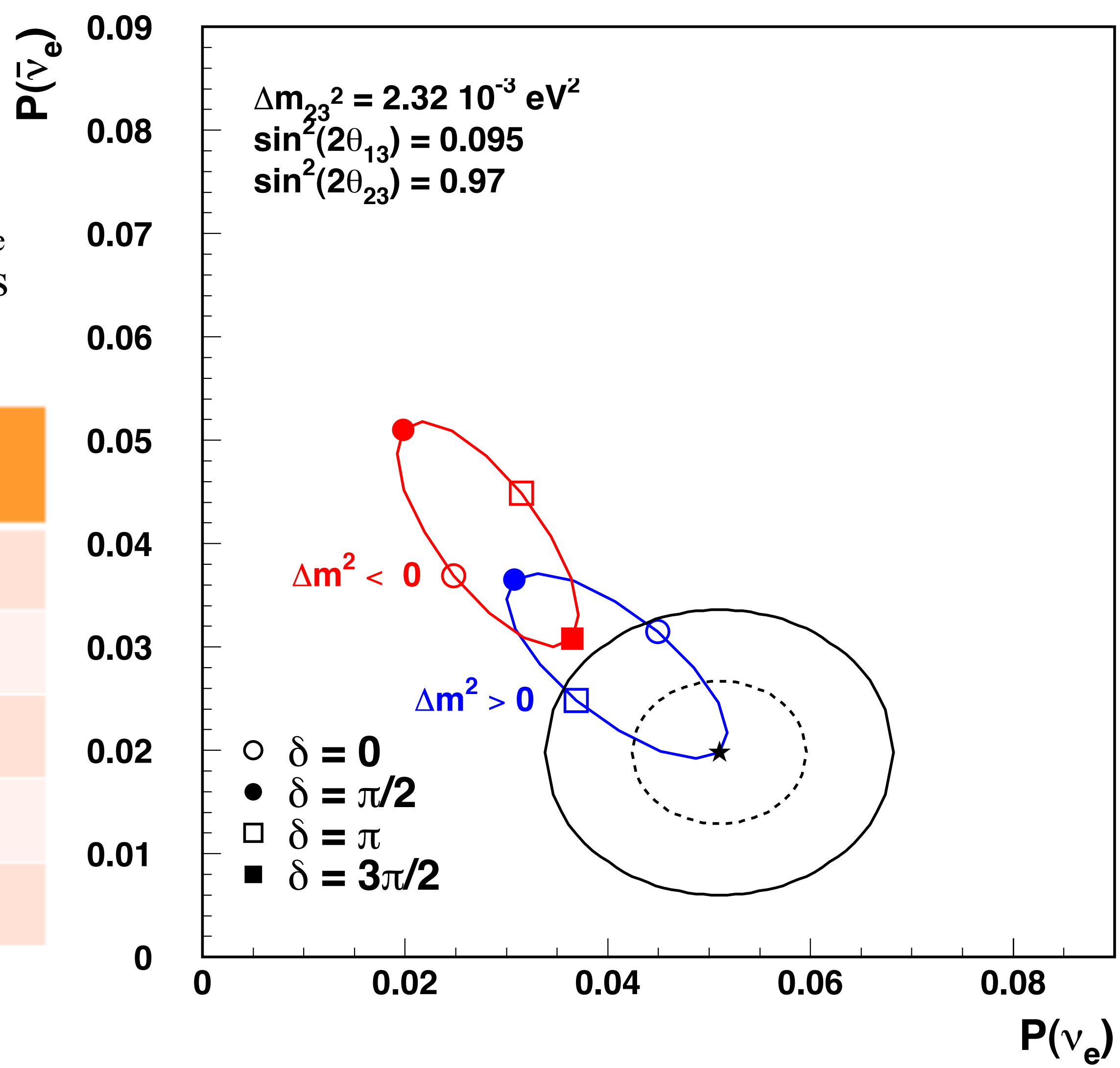


$\overset{(-)}{\nu}_e$ Appearance

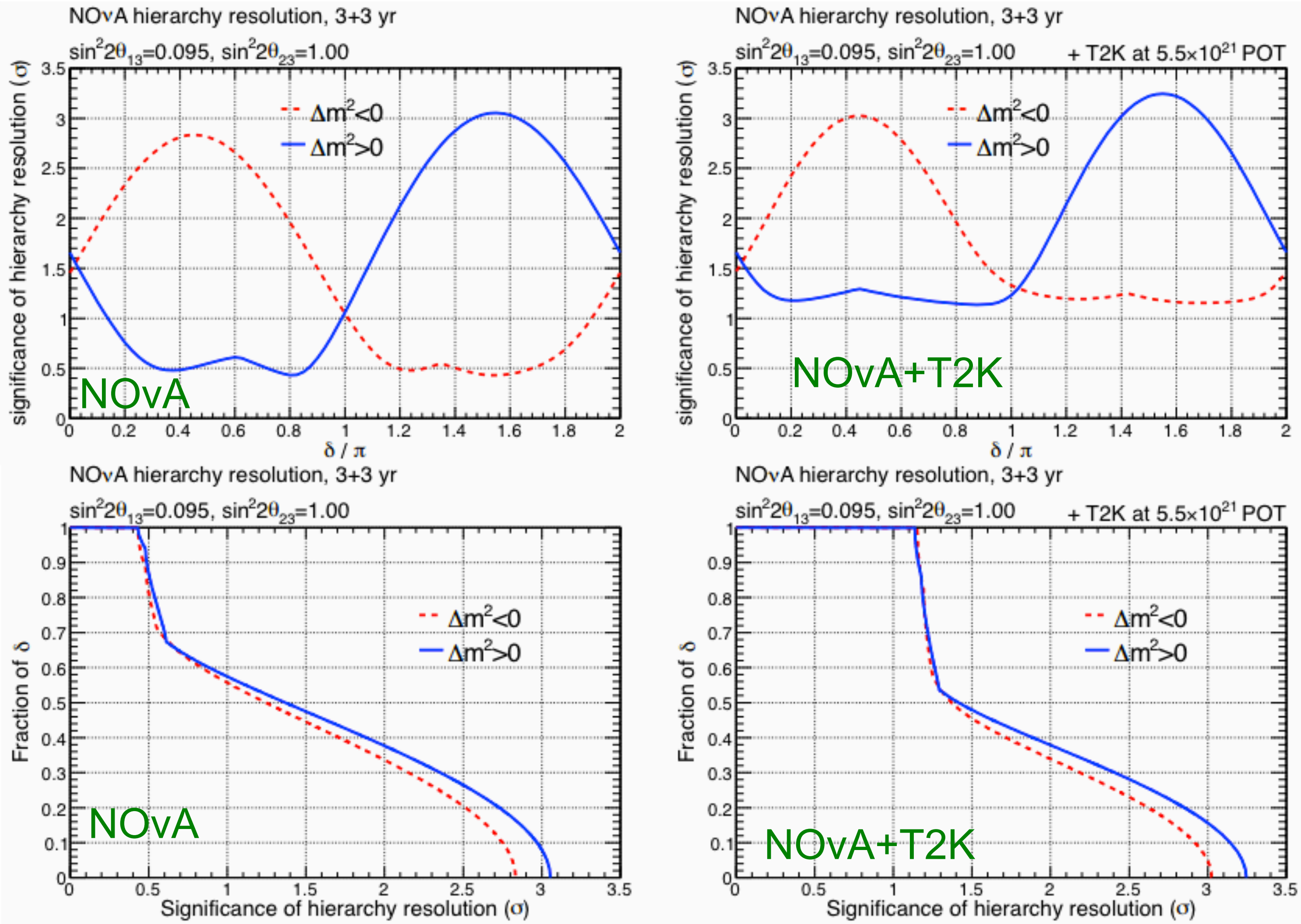
1 and 2 σ Contours for Starred Point

Example of event counts after ν_e selection for 3 years of neutrinos + 3 years of anti-neutrinos

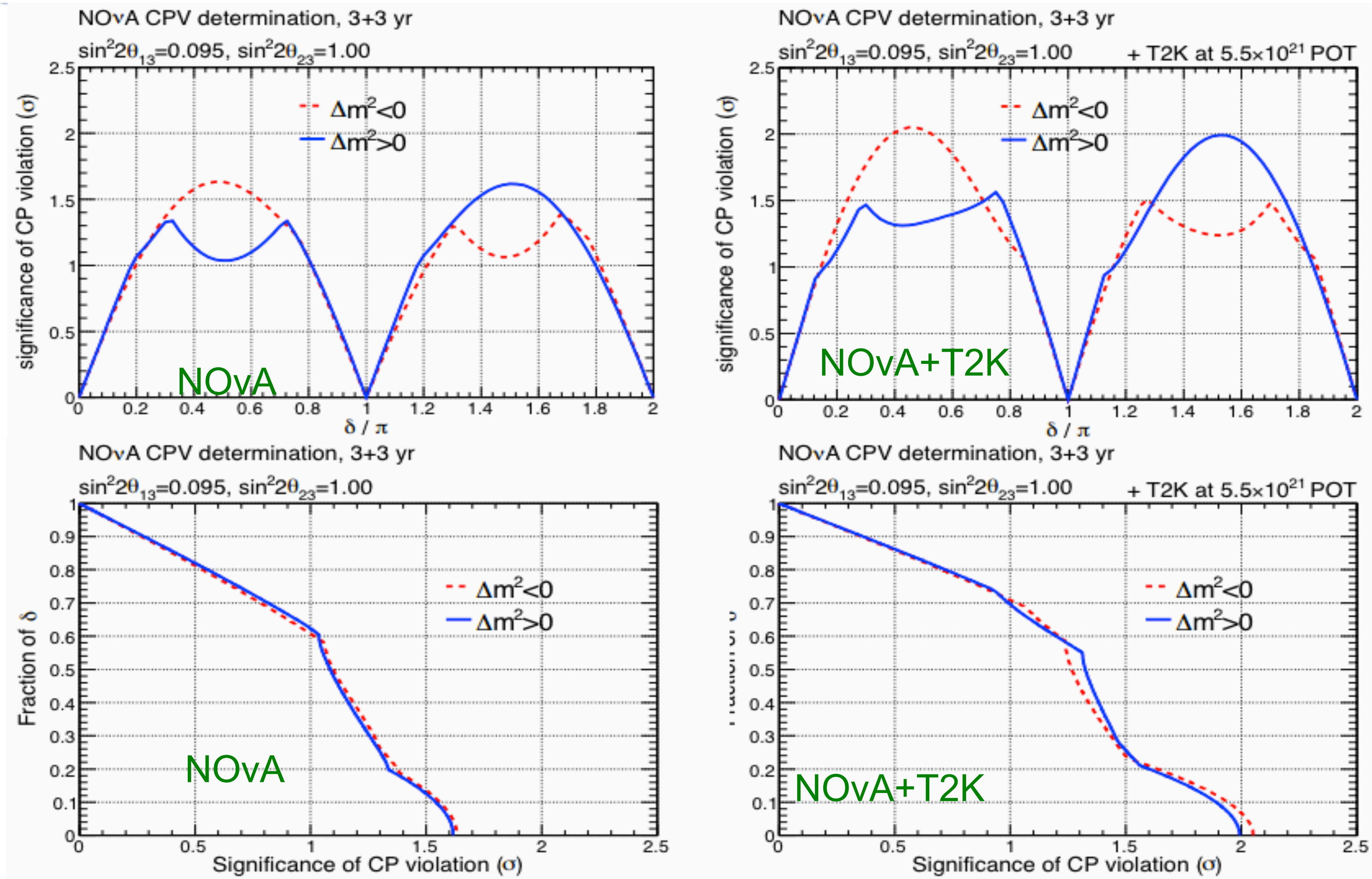
Events ($\sin^2(2\theta_{13})=0.095$)	ν	anti-ν
NC	19	10
ν_μ CC	5	<1
beam ν_e	8	5
Tot. BG	32	15
Signal	68	32



Mass Hierarchy Sensitivity



δ_{CP} Sensitivity



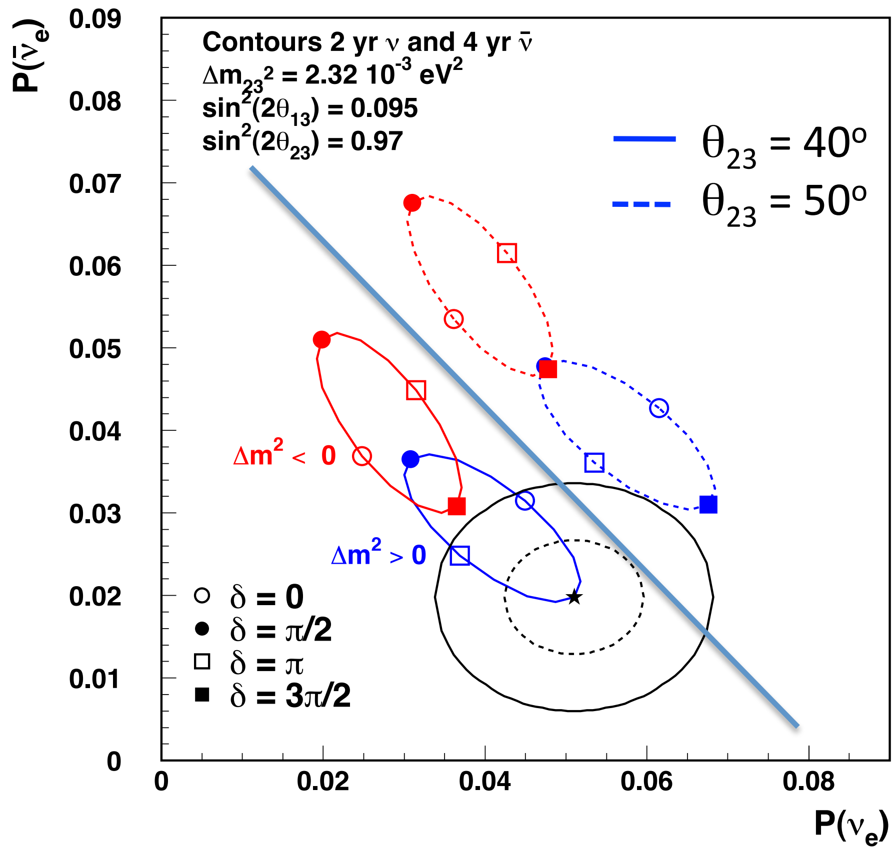
θ_{23} Octant

Currently there is an ambiguity in θ_{23} because atmospheric neutrino experiments measured ν_μ disappearance, which is sensitive to

$$\sin^2 2\theta_{23}$$

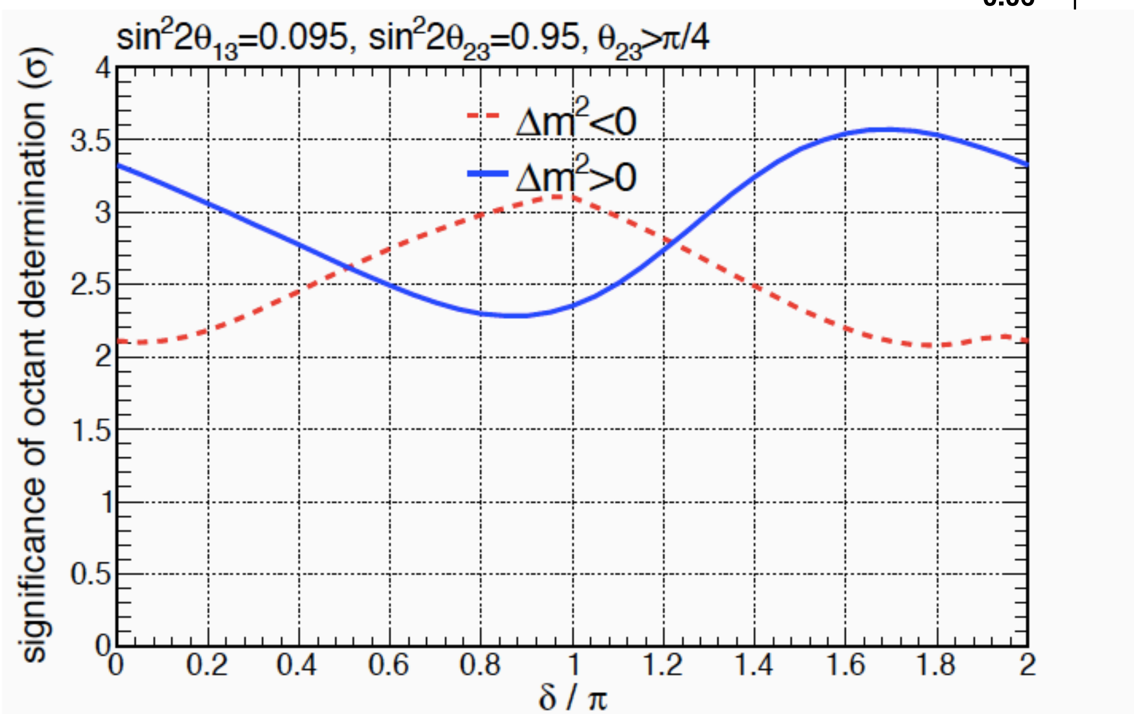
NOvA will have a sensitivity for resolving whether $\theta_{23} > \pi/4$ *or* $\theta_{23} < \pi/4$

1 and 2 σ Contours for Starred Point

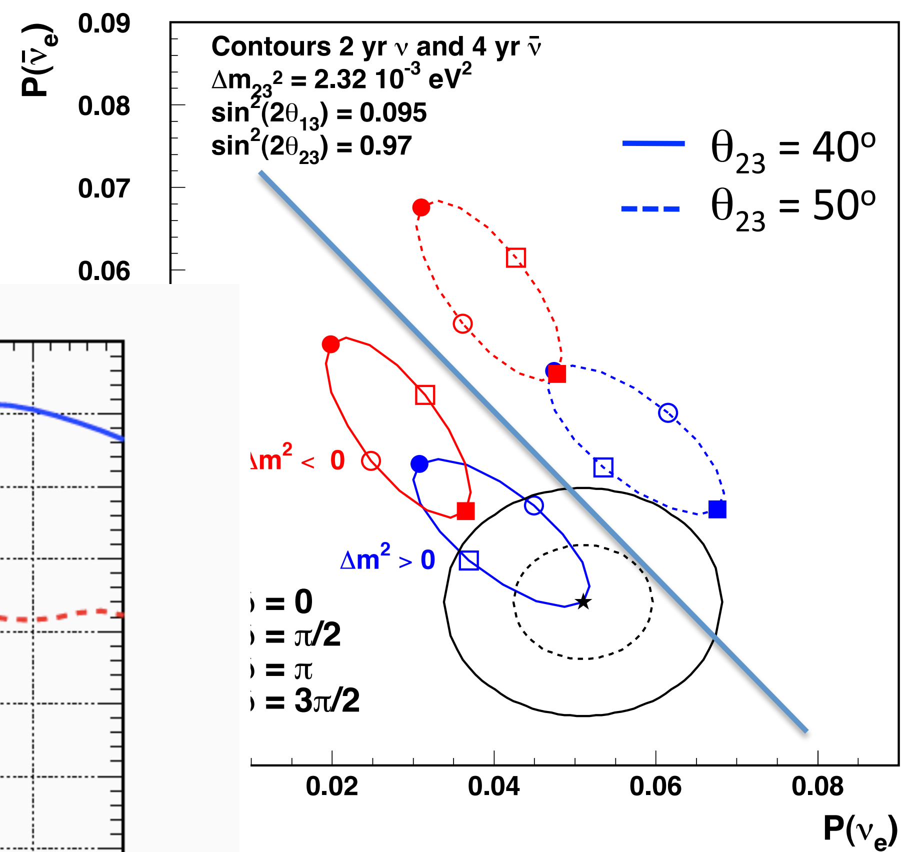


θ_{23} Octant

Sensitivity to determine the θ_{23} octant:



1 and 2 σ Contours for Starred Point

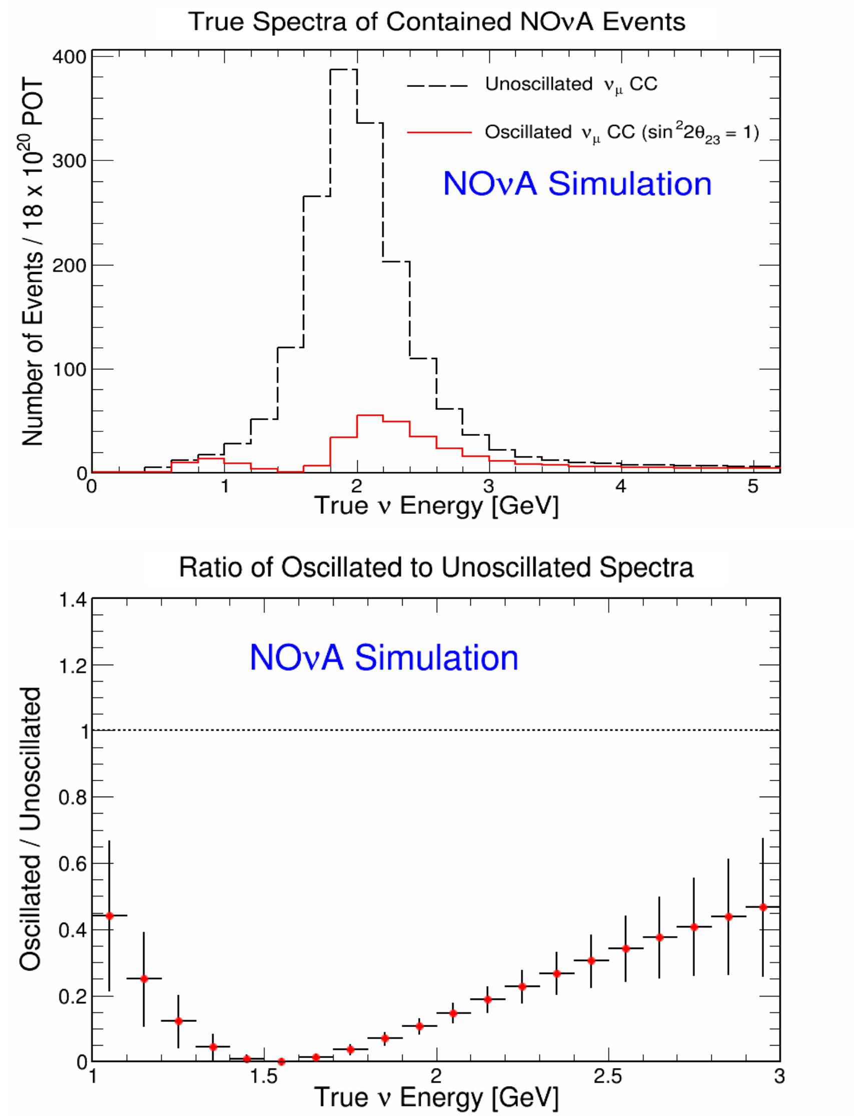


ν_μ Disappearance Sensitivity

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\Theta_{23})\sin^2\left(\frac{1.27\Delta m_{32}{}^2 L}{E}\right)$$

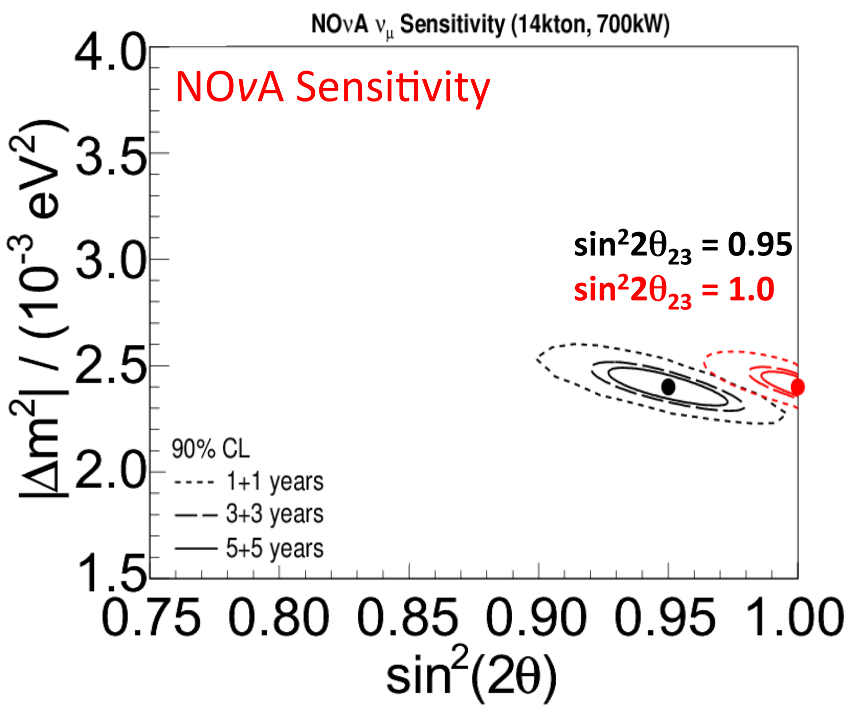
The position of the peak for unoscillated ν_μ rates energy spectrum (~2 GeV) is close to the first oscillation minimum at L=810 km.

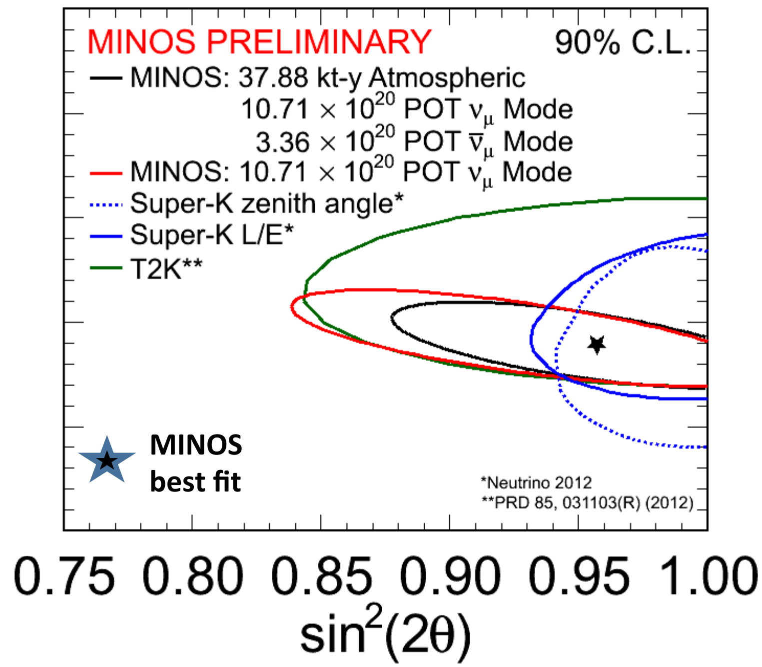
This provides a great sensitivity to both Δm^2_{32}, $\sin^2 2\theta_{23}$



ν_μ Disappearance Sensitivity

An example of a measurement





NOvA can greatly improve the knowledge of $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$

Status

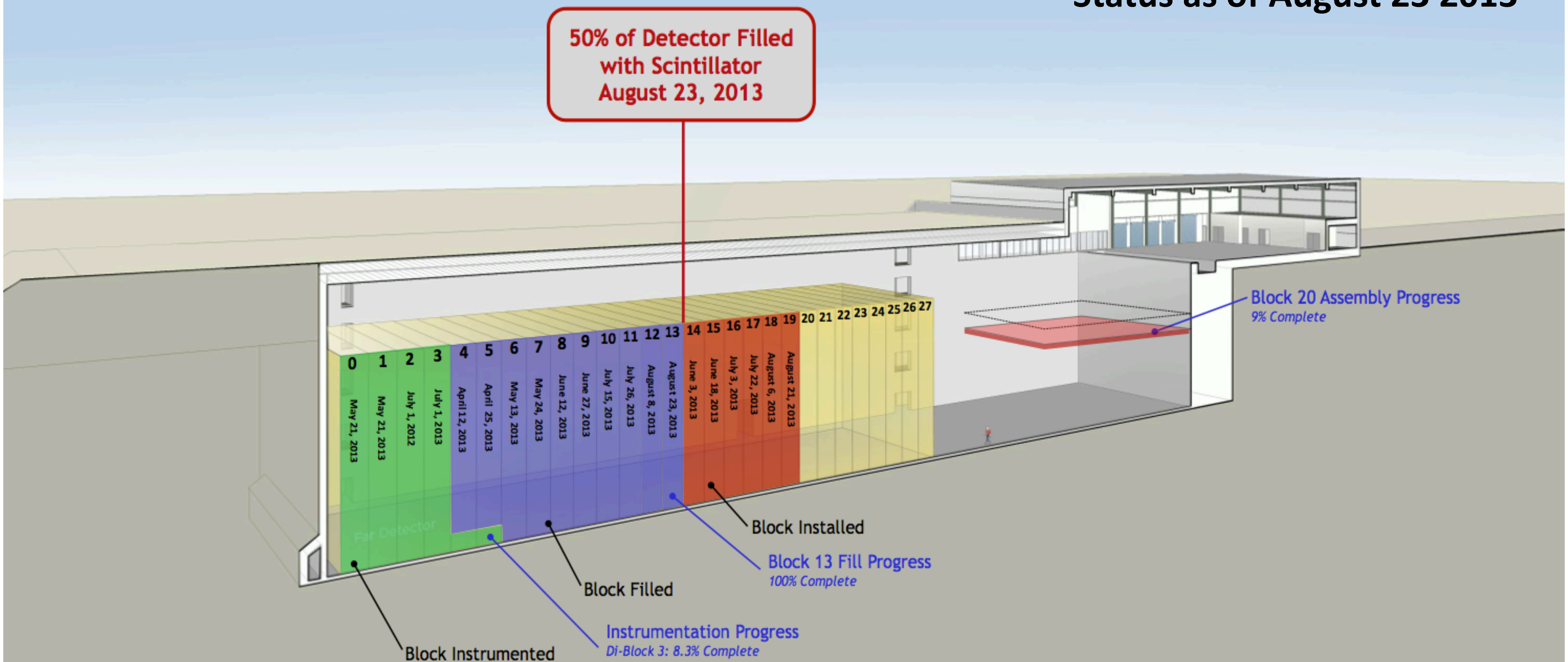
Far Detector Construction

Far Detector Construction

Far Detector Construction

Far Detector Construction

Status as of August 23 2013



14 kilotons = 28 NOvA Blocks

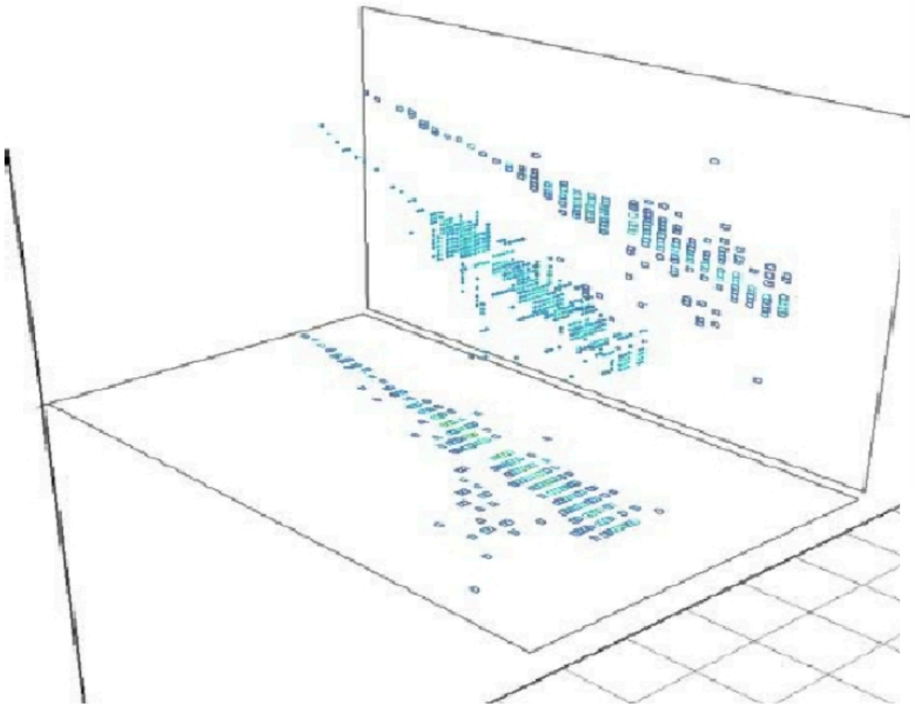
20 blocks of PVC modules are assembled and installed in place

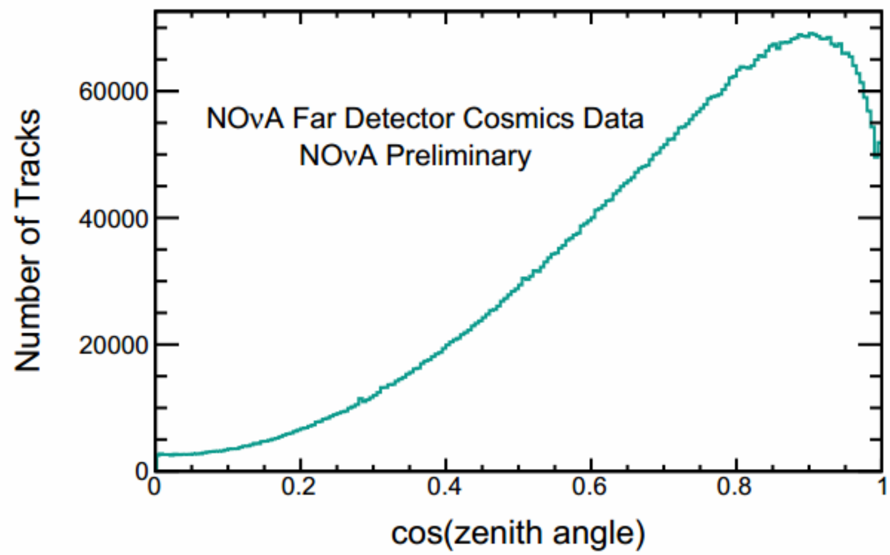
14.00 blocks are filled with liquid scintillator

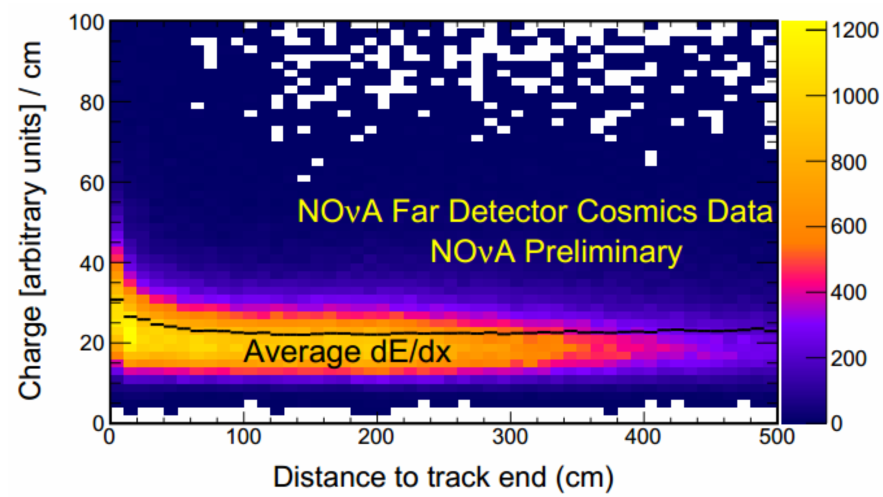
4.17 blocks are outfitted with electronics

Far Detector Cosmic Ray Data

One of the first cosmic events observed in the Far Detector



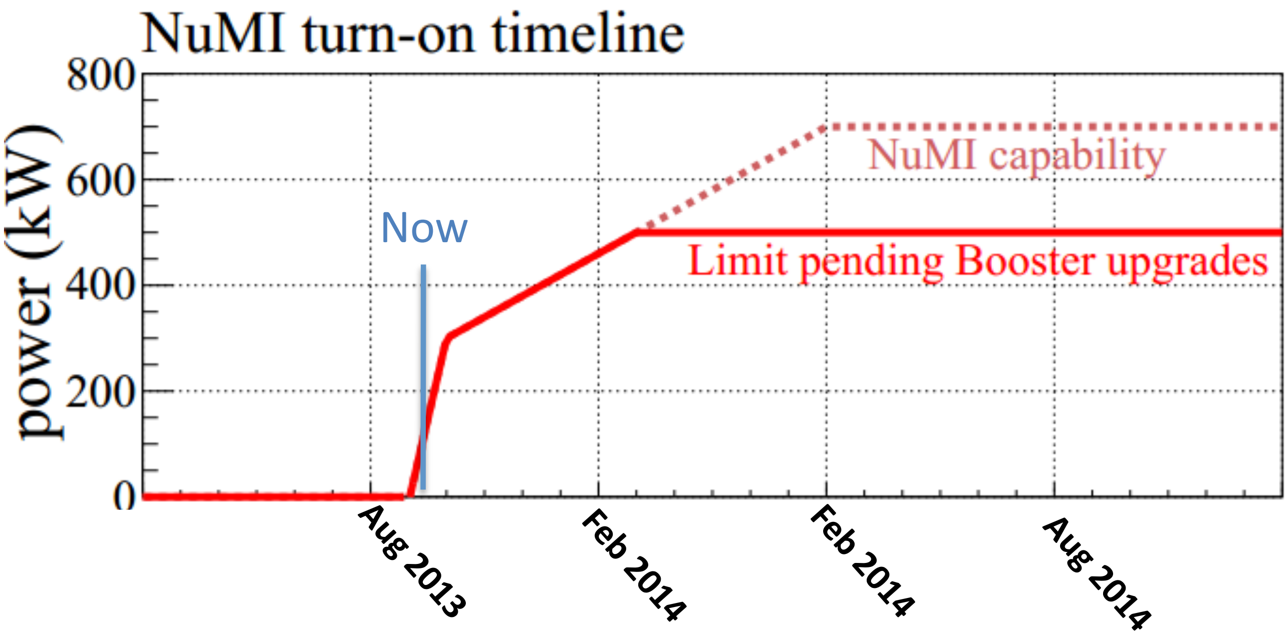




•First Cosmic events are observed in the Far Detector

•Calibrations are being performed

Beam Data



- Fermilab has completed a series of upgrades to the accelerator complex and NuMI beamline to increase the power capability from 300kW to 700kW.

- **First beam on September 4, 2013**

- Need Booster upgrades to reach 700kW

- Started looking for neutrinos!

Conclusions

- NOvA is a leading HEP experiment in the US looking for $\nu_\mu \rightarrow \nu_e$ oscillations.
- NOvA Far Detector construction is going well. 70% of the blocks are put in place, 50% filled with scintillator and 15% is instrumented .
- Analyzing cosmic data, performing calibrations.
- First beam data started on September 4, 2013. Analyzing data to find the neutrino beam signal.
- *Stay Tuned!*

Thank You

NOvA Main Webpage: http://www-nova.fnal.gov/

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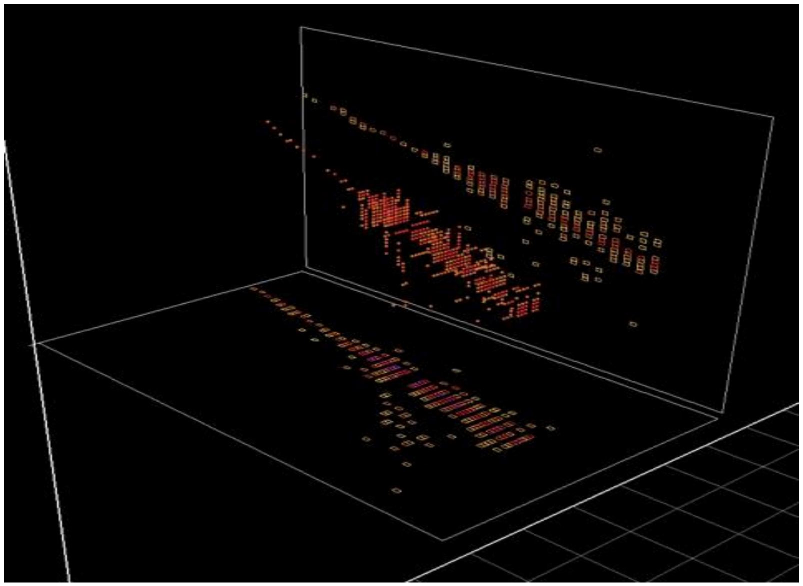
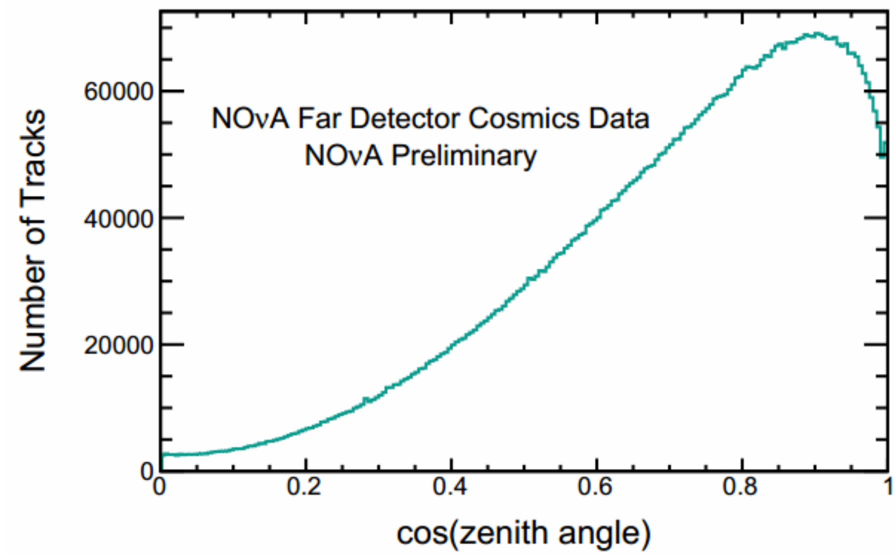
Like **us on**

BACKUPS

Far Detector Cosmic Ray Data

One of the first cosmic events observed in the Far Detector





•First Cosmic events are observed in the Far Detector
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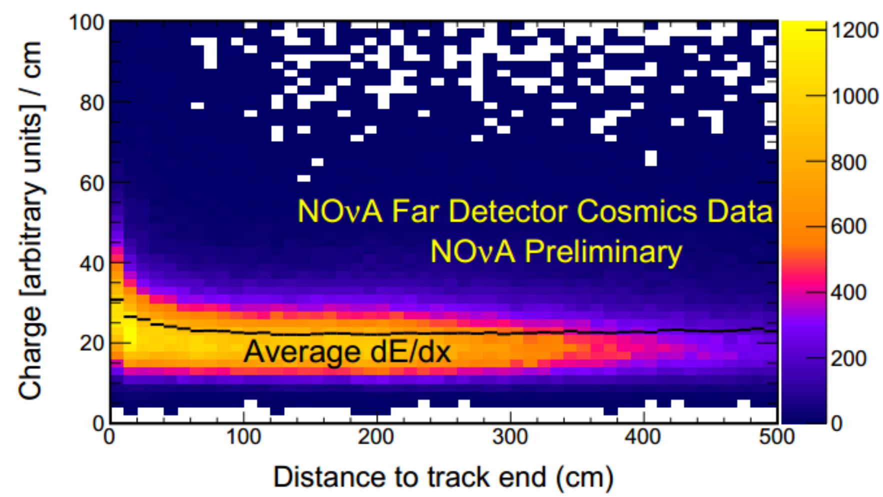
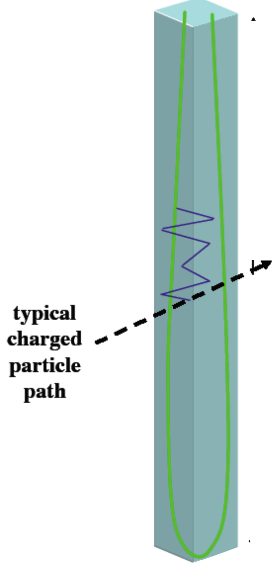
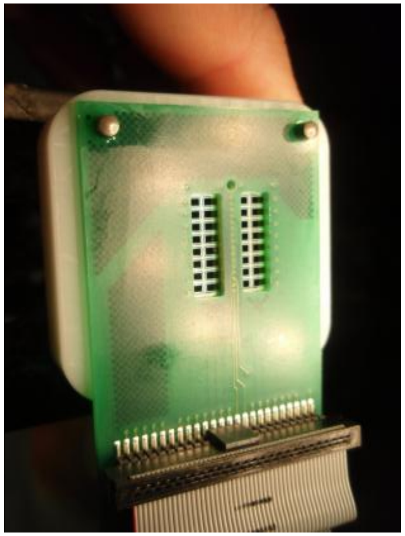


Electronics

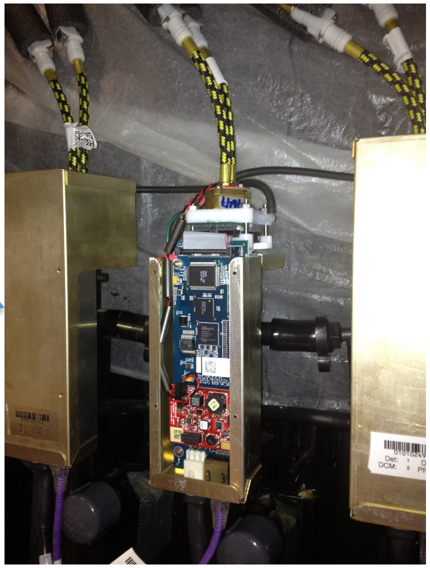


End of Fibers

Avalanche photo-diode (APD)

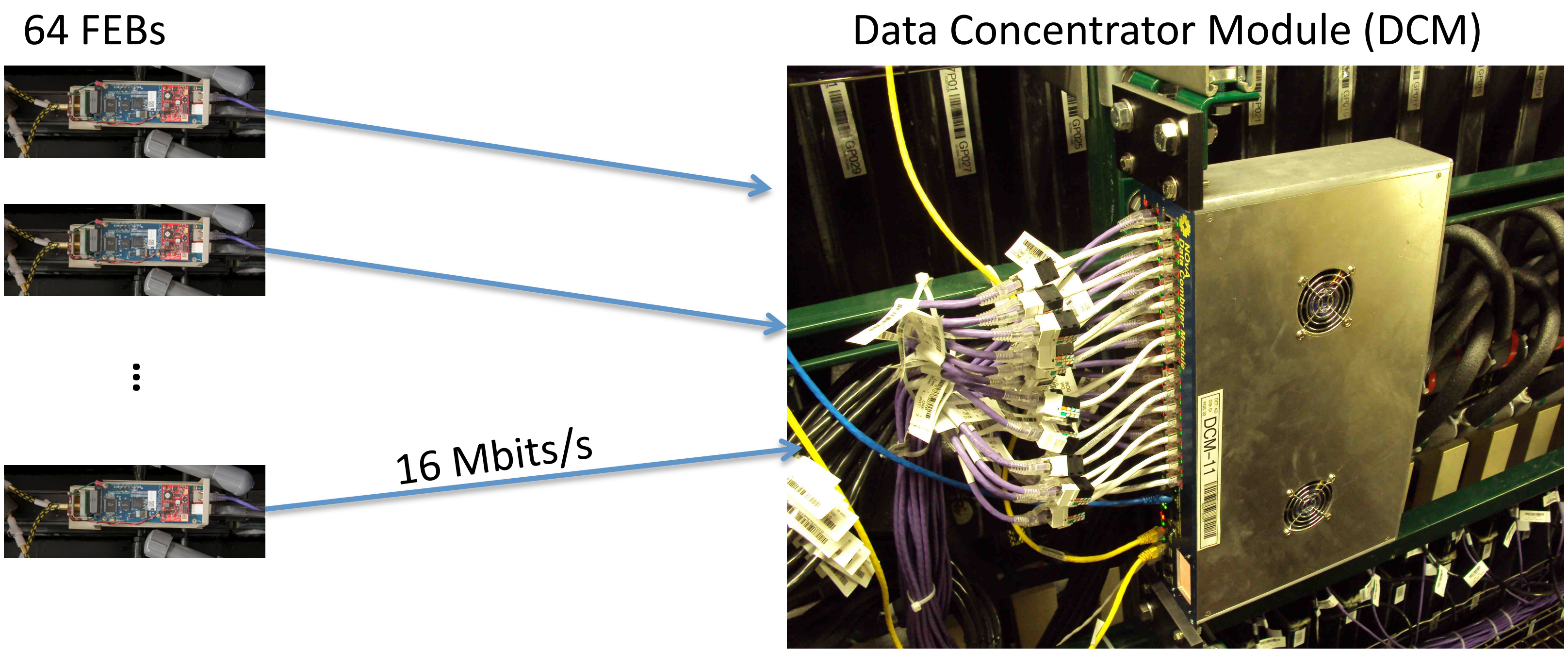


Front-end-board (FEB)



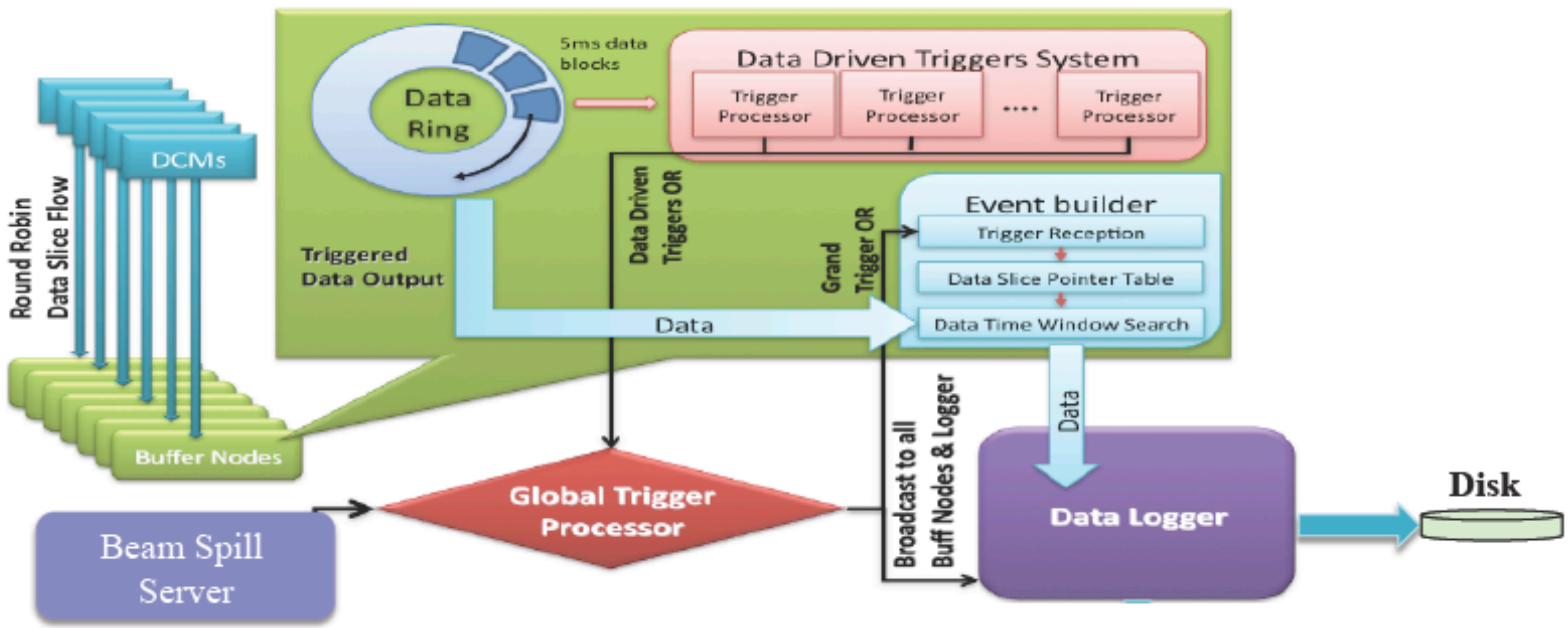
- Cell readout via looped WLS fiber to APD sensor
  - APD costs about $10 per channel, has gain of 100, actively cooled to to -15ºC
- FEB serves several purposes
  - Low-noise ASIC amplifier to maximize the sensitivity to small signals.
  - Analog-to-digital converter samples each pixel with a frequency of 2 MHz (8 MHz at Near Detector)
  - APD temperature control

Data Acquisition System

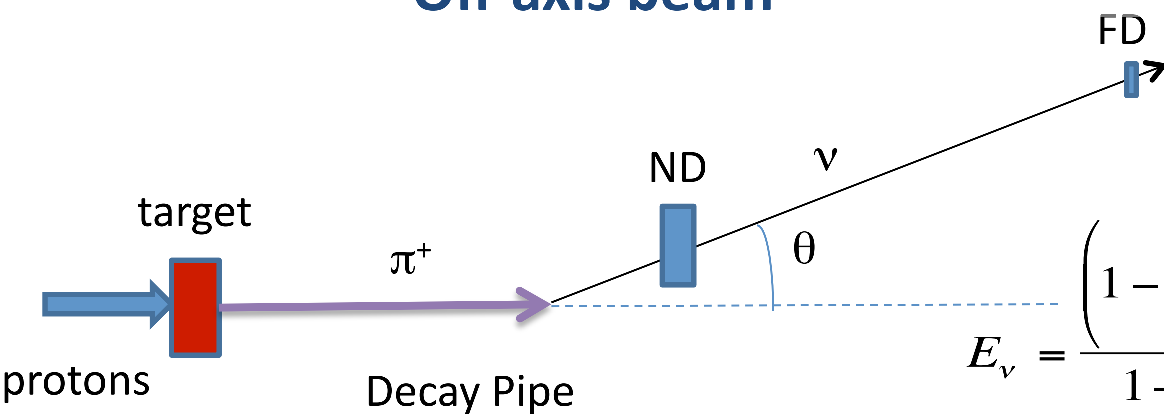


- 64 FEBs provide input to the Data Concentrator Module (DCM)
- DCM packetize the data and sends it through the Gigabit Ethernet to Buffer Nodes
- No data loss at this stage of the data transmission

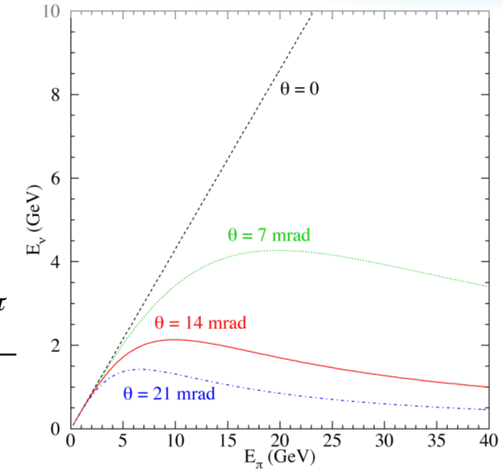
Data Acquisition System



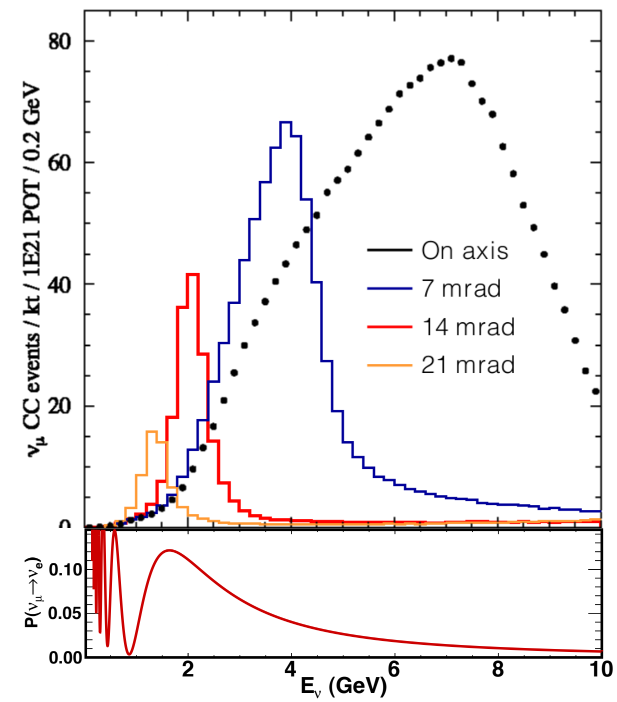
Off-axis beam



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



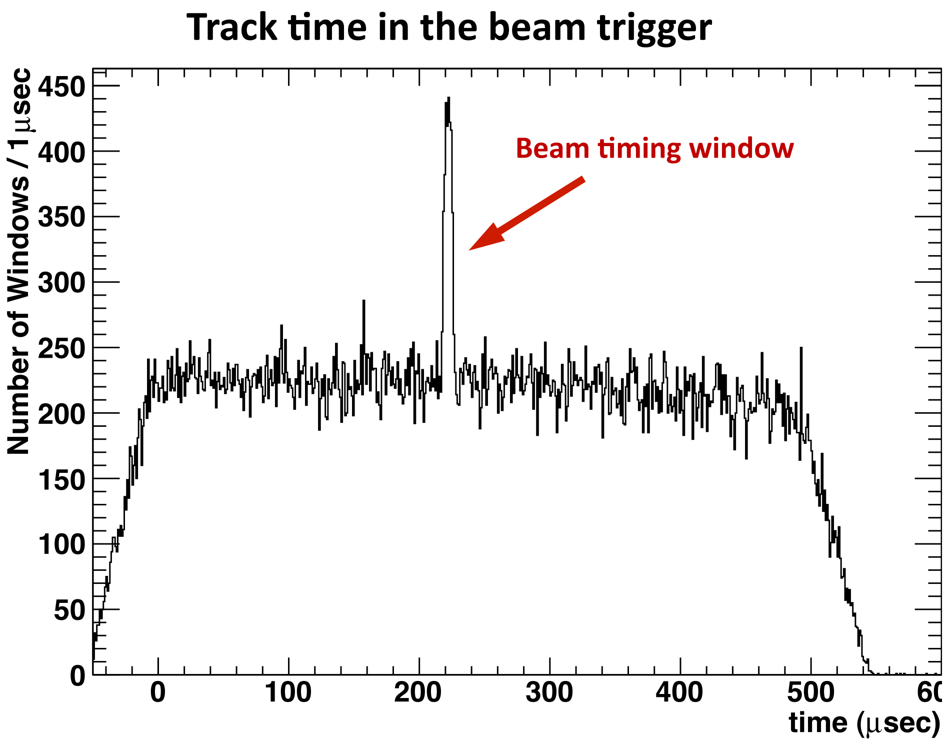
Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam. Close to the oscillation maximum.

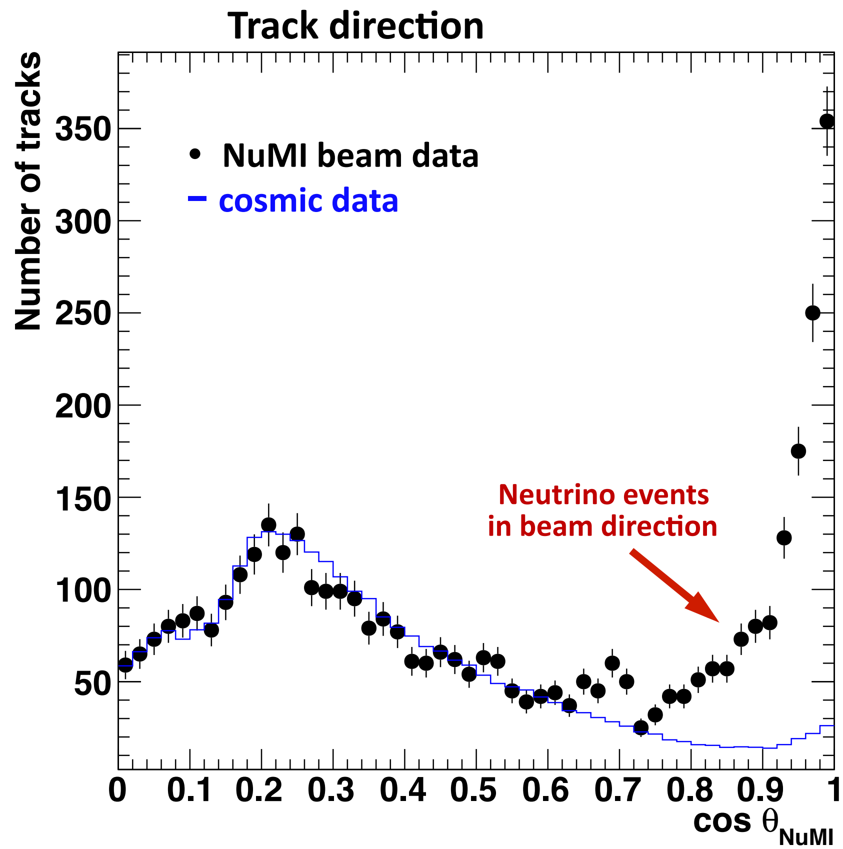


- **Enhanced 700 kW NuMI beamline (Currently 300 kW).**
- **Reduce cycle time from 2.2 to 1.3 seconds.**
- **Increased intensity/cycle with additional Booster batch.**
- **New horn and target.**
- **10μs beam pulse every 1.3 seconds.**
- **4.9e13 POT/pulse or 6e20 POT/year.**

Prototype Near Detector on Surface

NuMI Neutrinos (MINOS, Minerva, Argoneut)



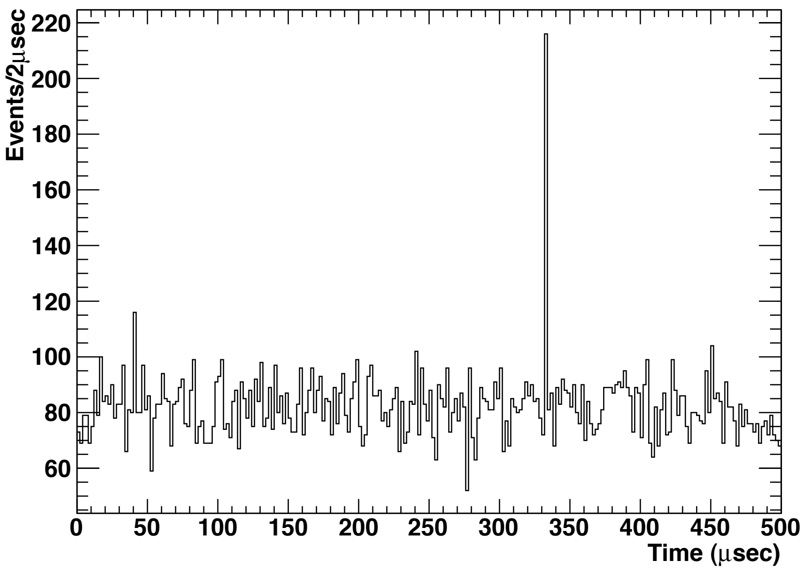


We do observe the neutrinos from the NuMI beamline

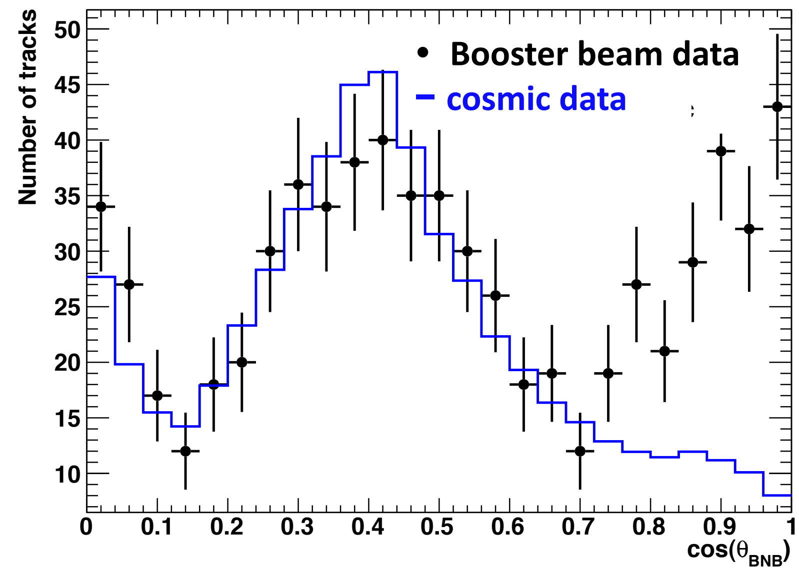
Prototype Near Detector on Surface

Booster Neutrinos (MiniBooNE, SciBooNE, MicroBooNE)

Track time in the beam trigger



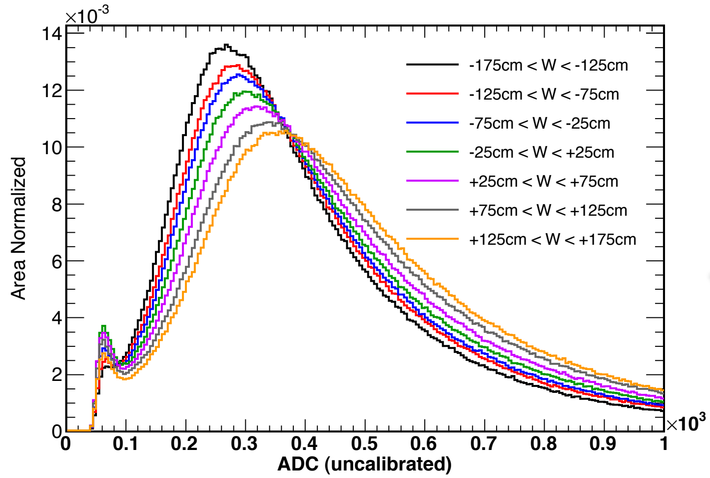
Track direction

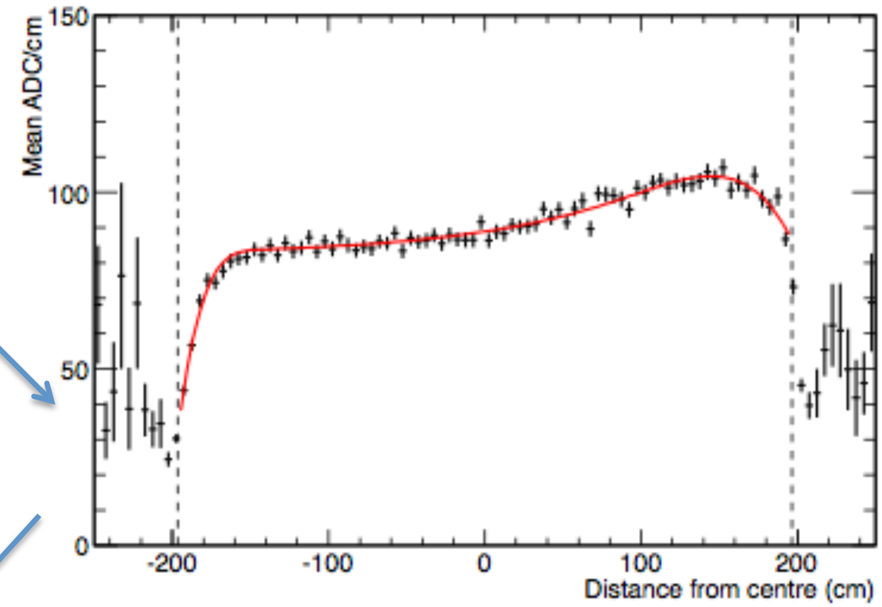


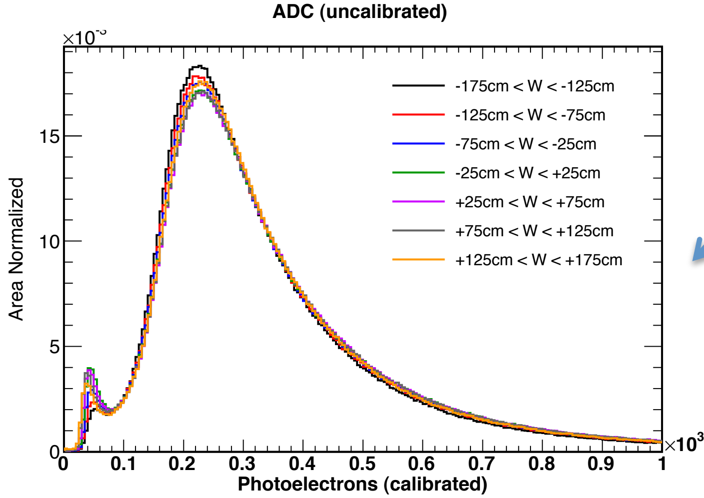
We do observe the neutrinos from the Booster beamline

Calibration. Attenuation.

Cosmic Data







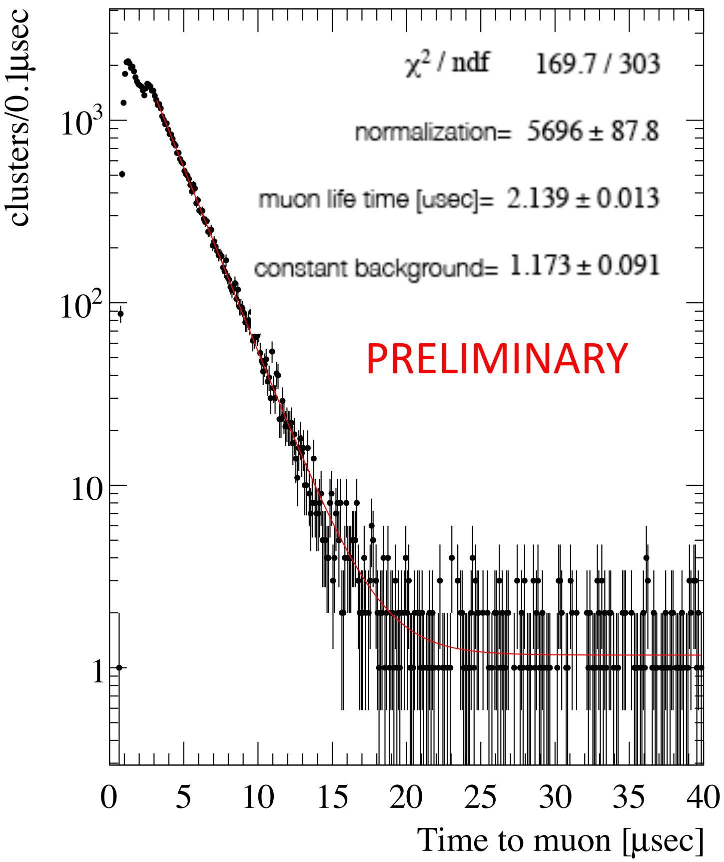
Top left: Path length-corrected muon response for different distances from fiber end for a single example cell

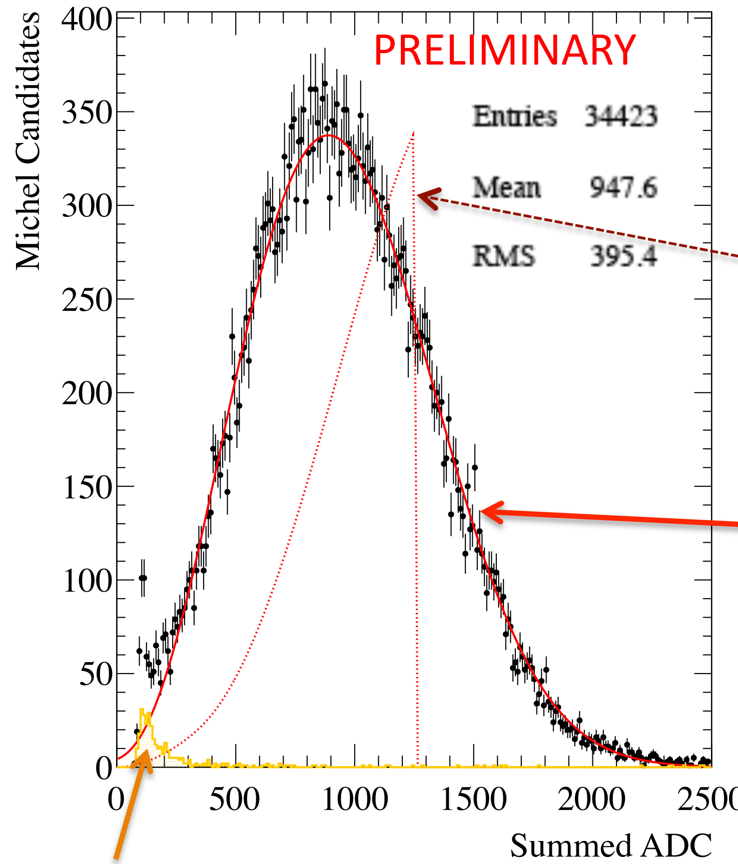
Above: Measured and fitted fiber attenuation for the example cell

Bottom left: Muon response after attenuation corrections

Calibration

Michel Electron Energy Spectrum



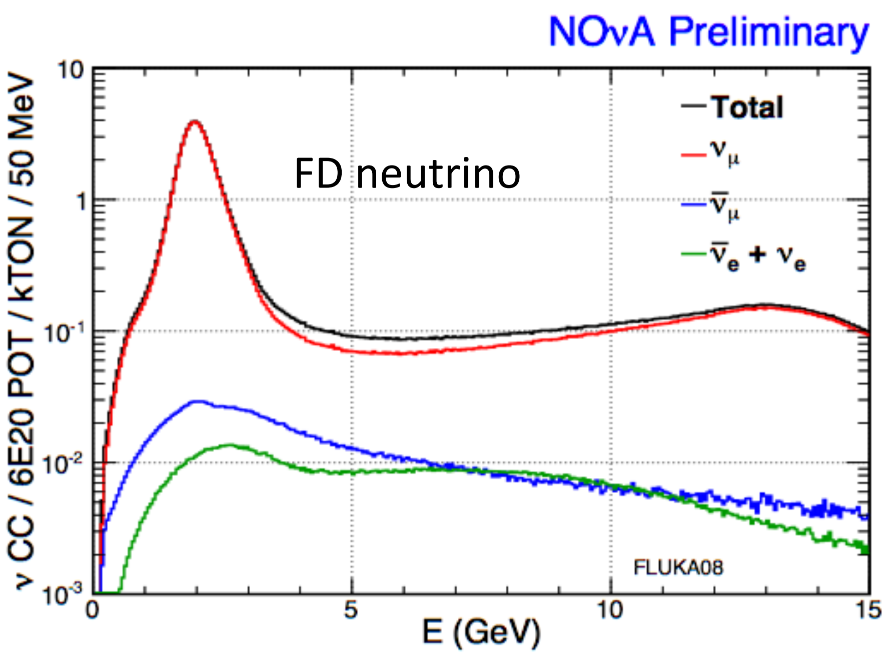


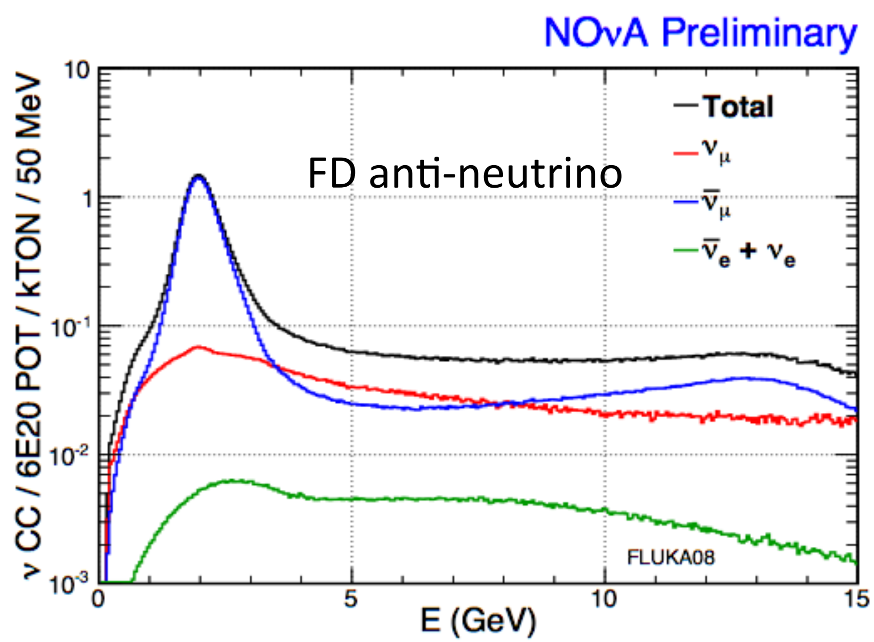
Michel Electron Spectrum

Michel Electron Spectrum smeared with 32.5% resolution

Random coincidence events that are matched to muons 20 seconds prior to the event.

Neutrino flux





- The NOvA off-axis beam has a peak in the 1-3 GeV signal region with 1.6% wrong sign contamination and 0.6% beam ν_e
- For anti-neutrino configuration has only 10% wrong sign contamination and 0.8% beam ν_e

$\overset{(-)}{\nu}_e$ Appearance

- NOvA measures the probability of ν_e appearance in a ν_μ beam:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$$

- $\sin^2(2\theta_{13})$ has been measured which allows us to make measurements of δ_{CP} and mass hierarchy.
- Note that we can improve θ_{23} measurement from ν_μ disappearance.
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy, i.e the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running.

Sensitivity to δ_{CP} versus $\sin^2 2\theta_{13}$

•A Feldman-Cousins method was used

•*Results are consistent with secondary selection and cross-check method; agree with truth within ~1σ*