The NOvA Experiment

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Overview

- Neutrino Oscillations Overview
- NOvA Experiment Introduction
- Current Status
- Summary

Neutrino Mixing Matrix and Masses

atmospheric ν — **Mixed Term** — **solar ν**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing Matrix and Masses

atmospheric ν | **Mixed Term** | **solar ν**

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Atmospheric:

$$\Delta m^2_{31}=(2.45\pm0.009)\times10^{-3}eV^2$$

$$\sin^2\theta_{23}=0.51\pm0.06$$

Solar:

$$\Delta m^2_{21}=(7.59^{+0.20}_{-0.18})\times10^{-5}eV^2$$

$$\sin^2\theta_{12}=0.312^{+0.017}_{-0.015}$$

arXiv:1108.1376

Neutrino Mixing Matrix and Masses

atmospheric ν | Mixed Term | solar ν

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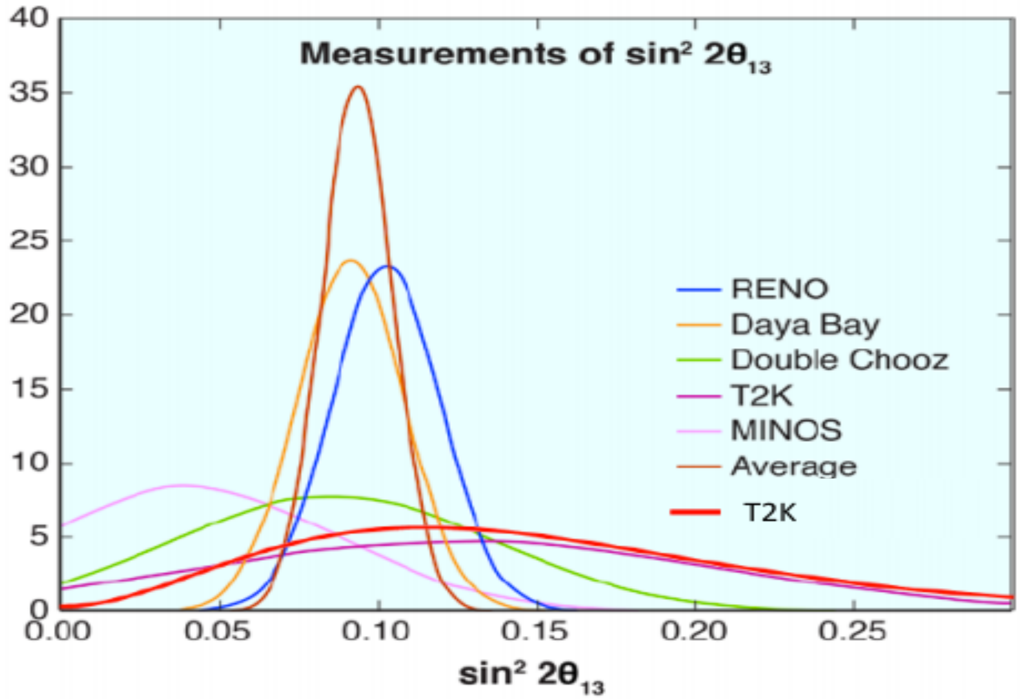
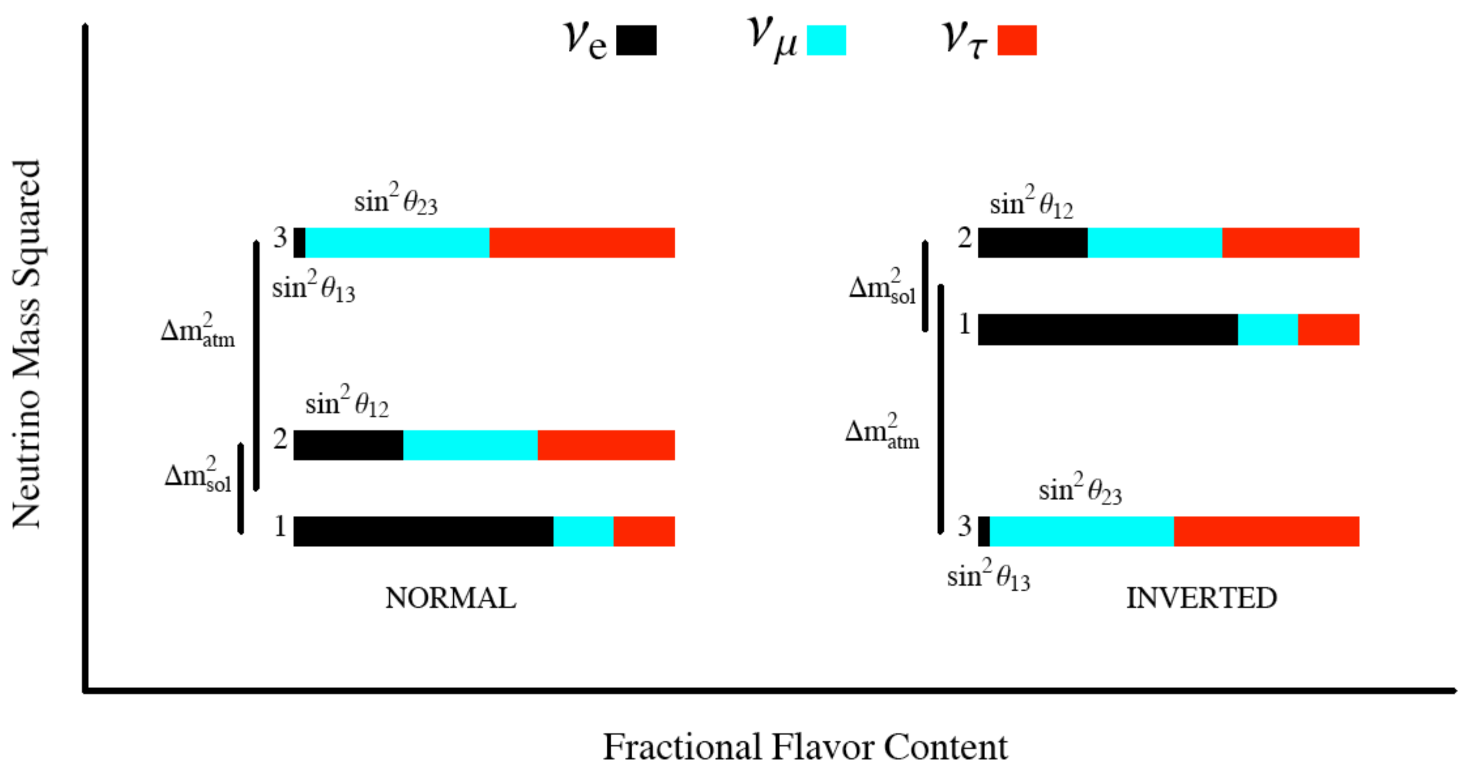


- Daya Bay 0.092 ± 0.017
  - ✓ arXiv:1203.1669v2 [hep-ex]
- RENO 0.113 ± 0.023 (revised)
  - ✓ arXiv:1204.0626v2 [hep-ex]
- Reactor Average
  - ✓ 0.099 ± 0.014
- Combined Average
  - ✓ 0.092 ± 0.012

Mass Hierarchy

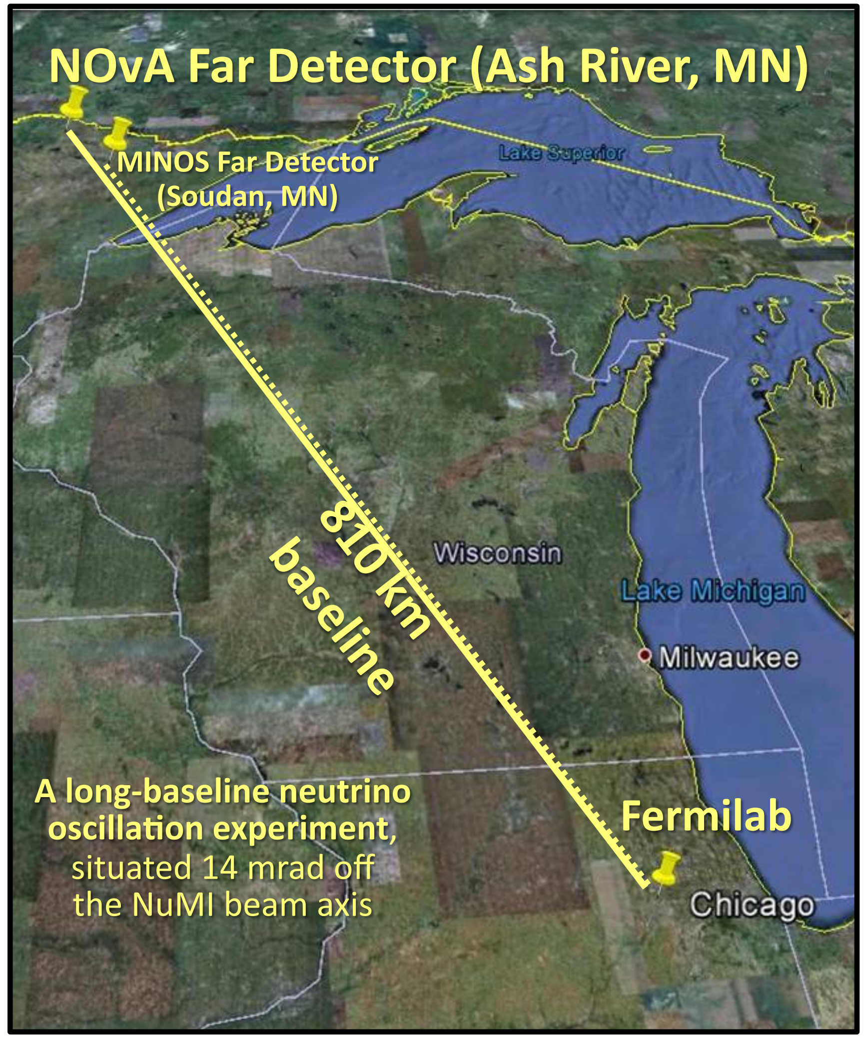


Currently the mass hierarchy is unknown

The NOvA Experiment

Long baseline neutrino oscillation experiment:

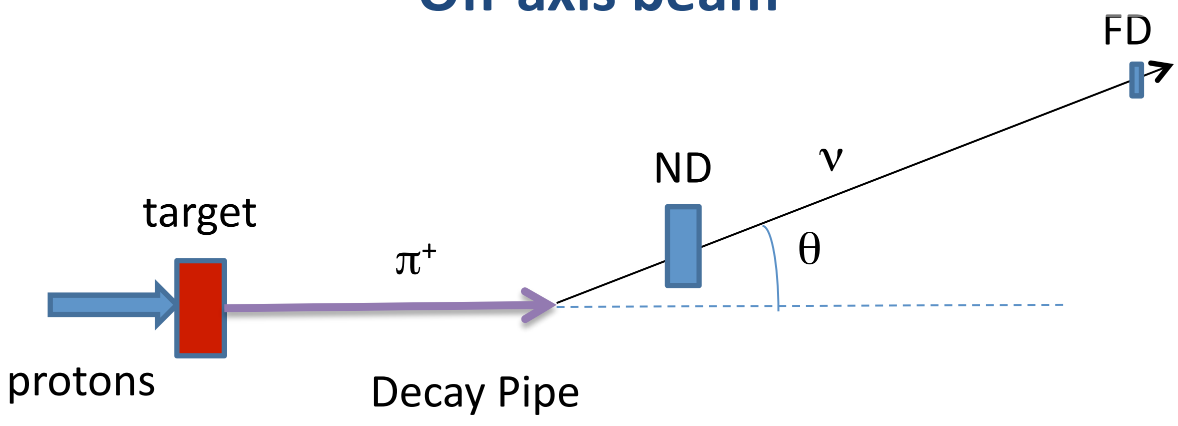
- Near and far detector pair.
- Off-axis in order to have a narrow neutrino flux with the energy peak is at 2GeV.
- 810 km baseline from Fermilab to Ash River, Minnesota.



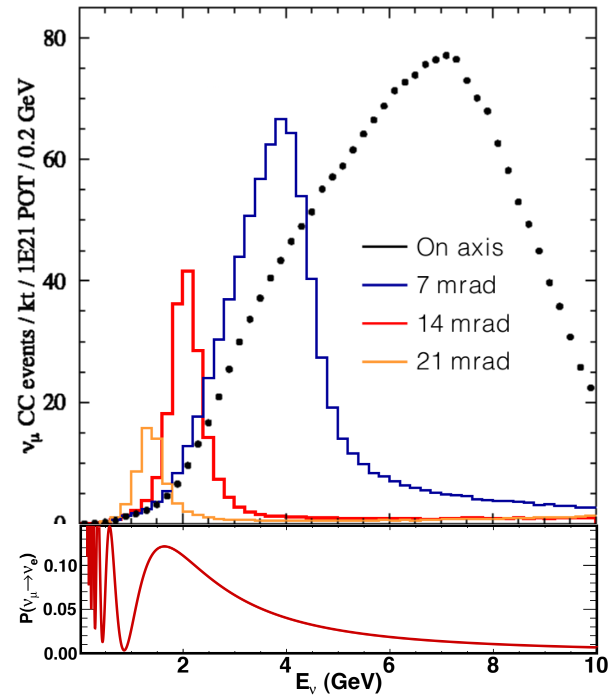
Goals:

- **Measure $\nu_\mu \rightarrow \nu_e$ oscillations.**
- precision measurements of $|\Delta m^2_{31}|$, θ_{23}.
- *determine mass hierarchy.*
- *constrain CP violating phase.*

Off-axis beam

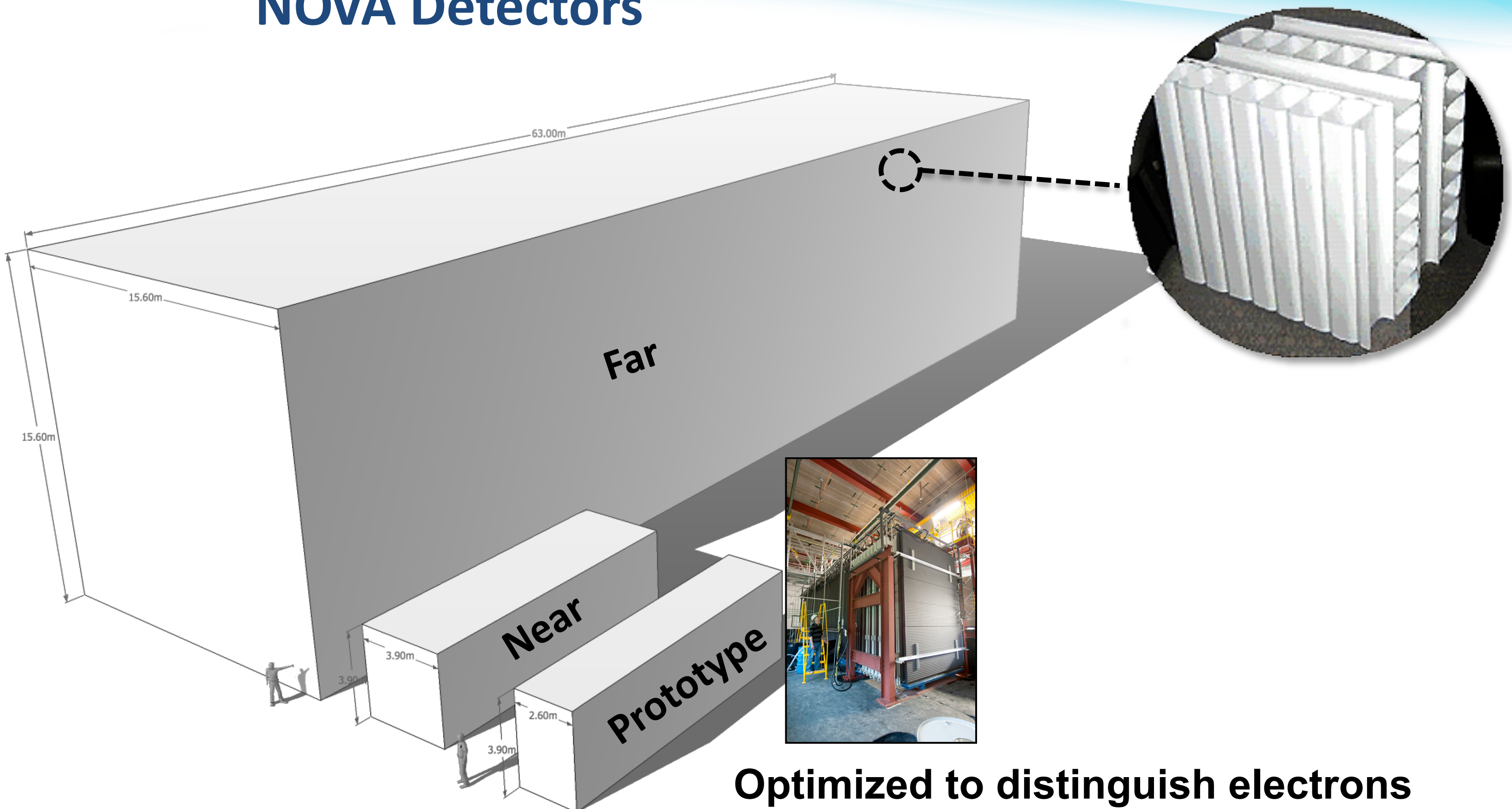


Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam. Close to the oscillation maximum.



- **Enhanced 700 kW NuMI beamline (Currently 300 kW).**
- **New horn and target.**

NOvA Detectors

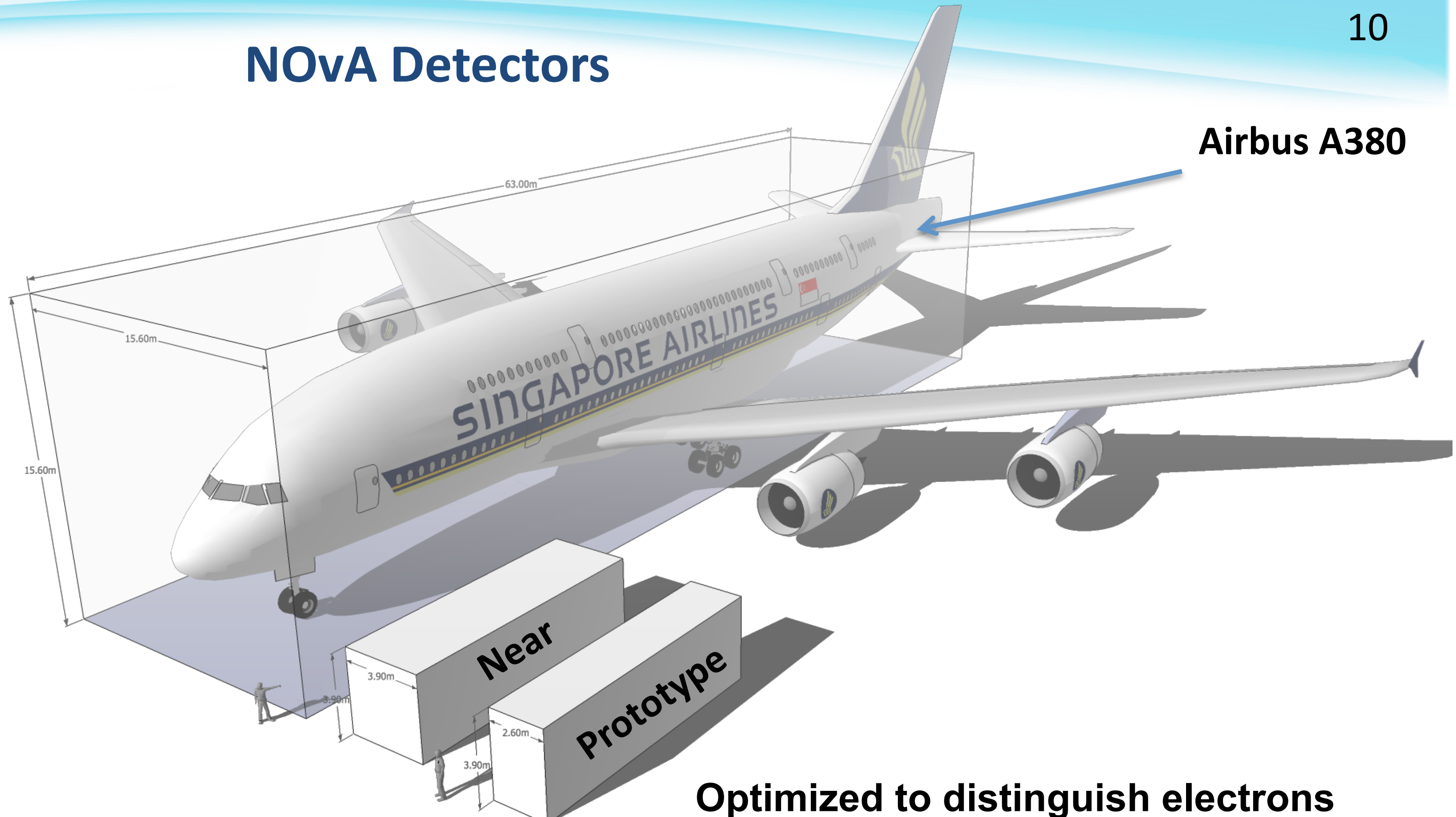


- A LARGE 14+ kton Far Detector
- A smaller Functionally equivalent Near Detector
  - Reduced systematic uncertainties

Optimized to distinguish electrons

- Highly segmented (alternating X/Y)
- 65% Active Volume
- Low Z materials (PVC and Scintillator) provide radiation length ~ 40 cm

NOvA Detectors



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- Highly segmented (alternating X/Y)
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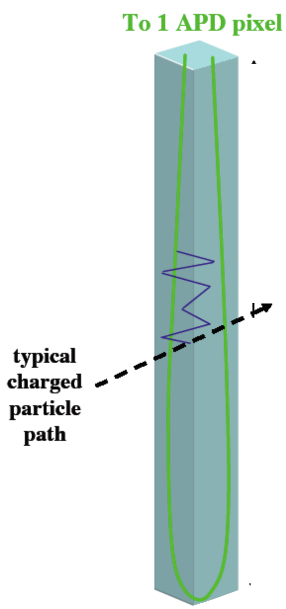
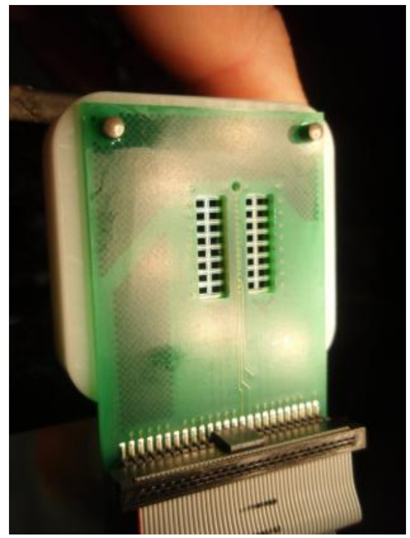
Electronics



End of Fibers

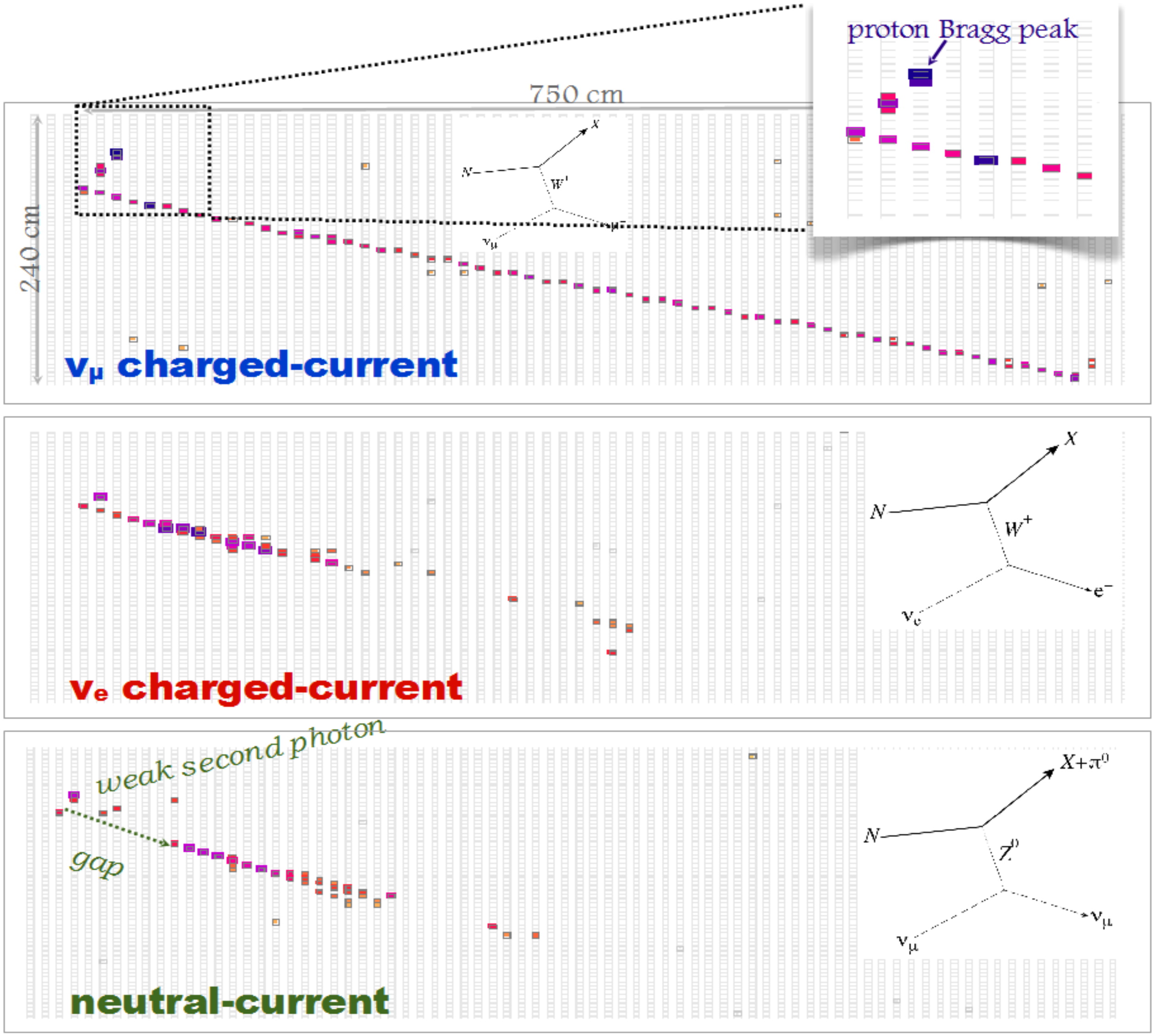
Avalanche photo-diode (APD)



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 -15°C
- 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

Simulated Event Signatures



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

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

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

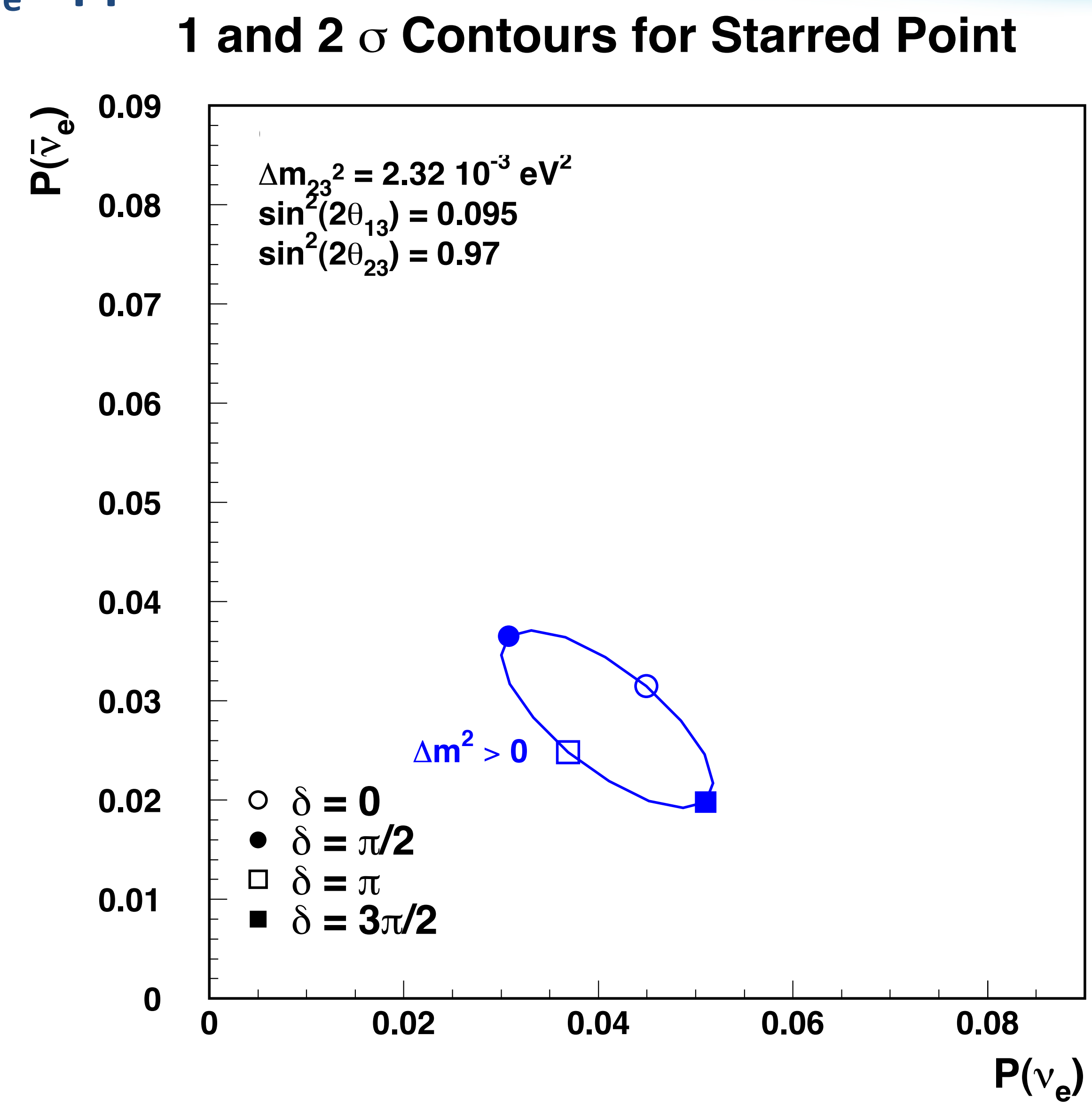
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$
$$+\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

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

- **$\sin^2(2\theta_{13})$** 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.

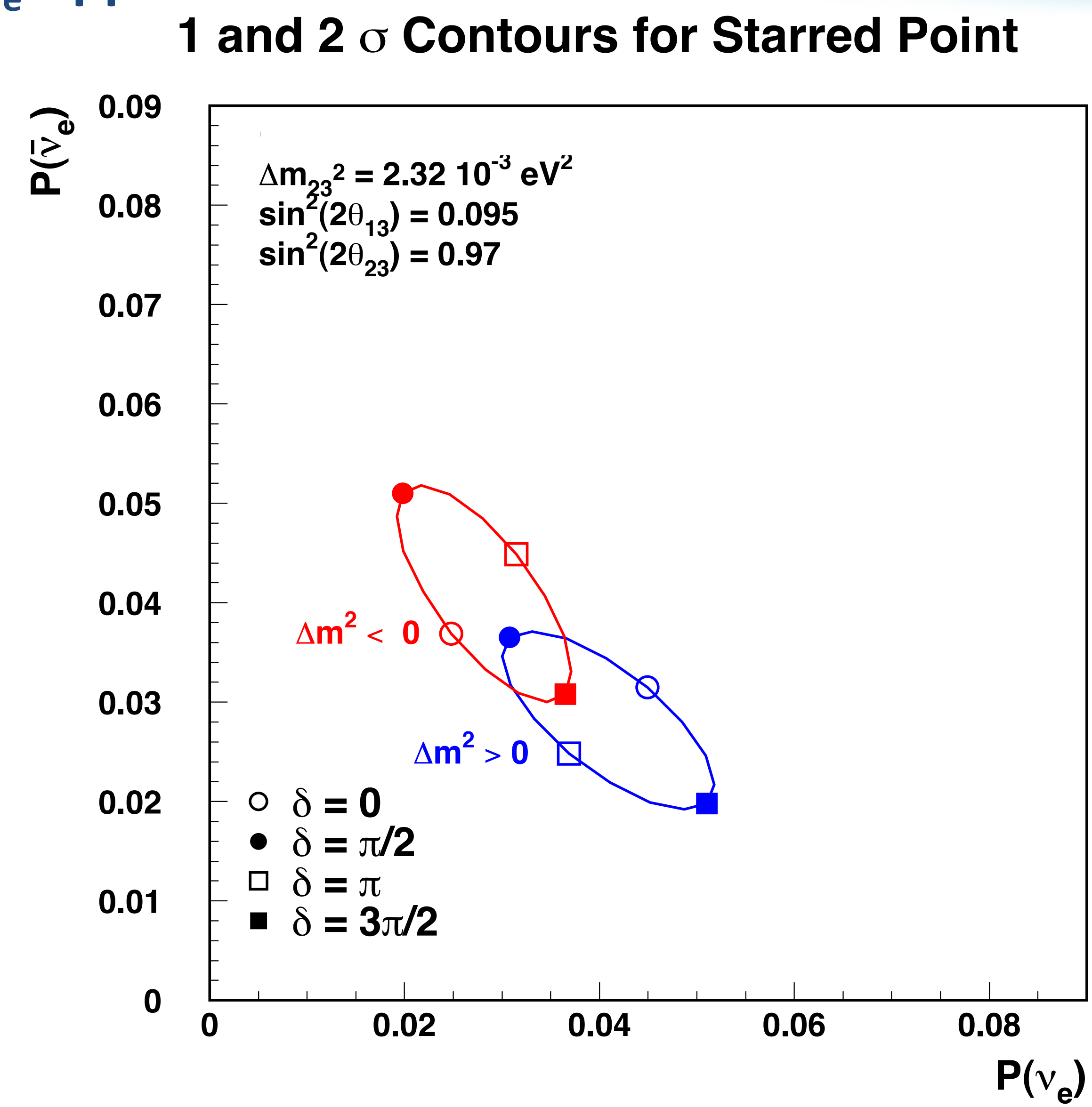
$\overset{(-)}{\nu}_e$ Appearance

Probability of oscillations for both ν_μ and $\bar{\nu}_\mu$ as a function of δ.



ICFP 2012

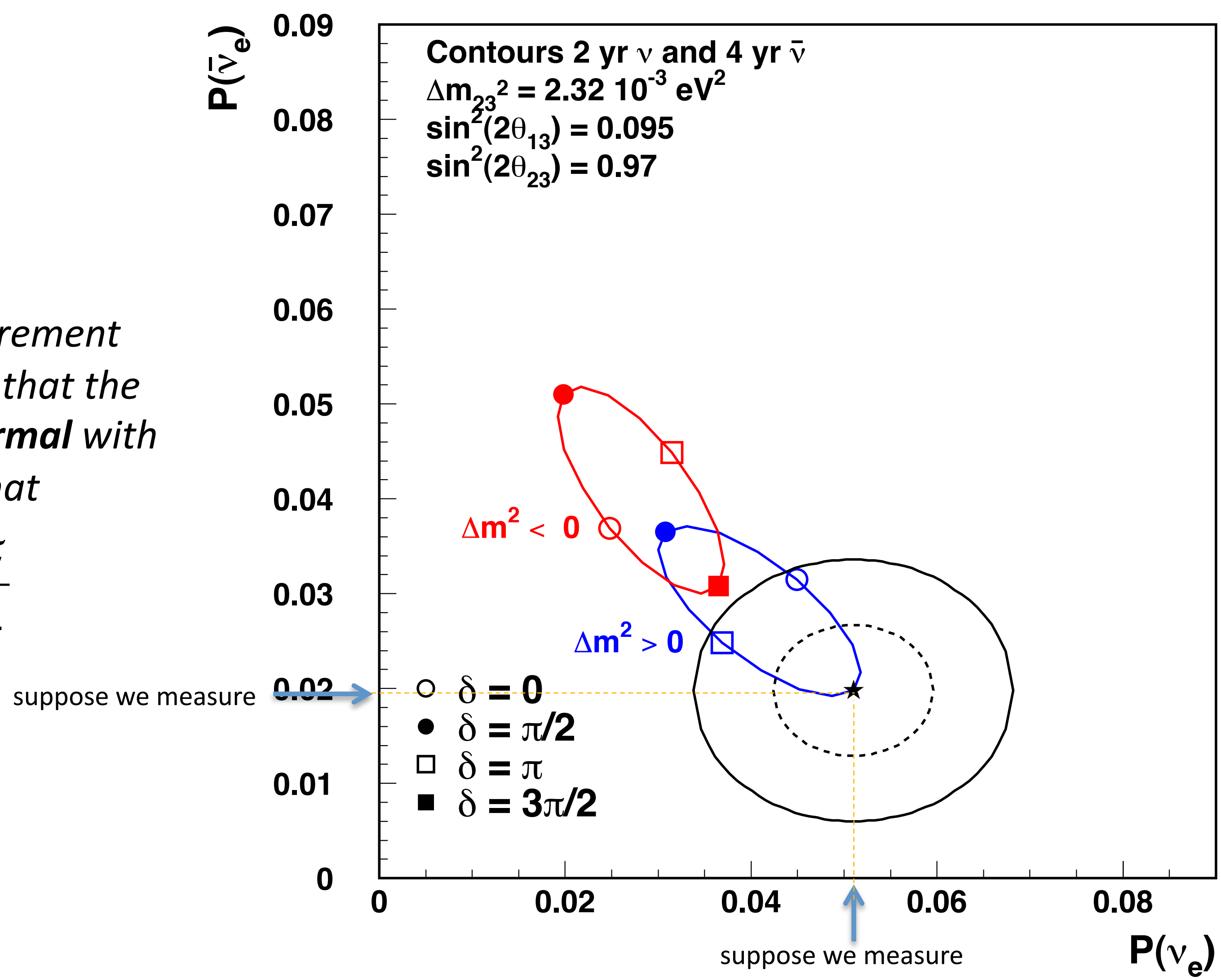
$\overset{(-)}{\nu}_e$ Appearance



Inverse mass hierarchy gives different values for the probabilities.

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

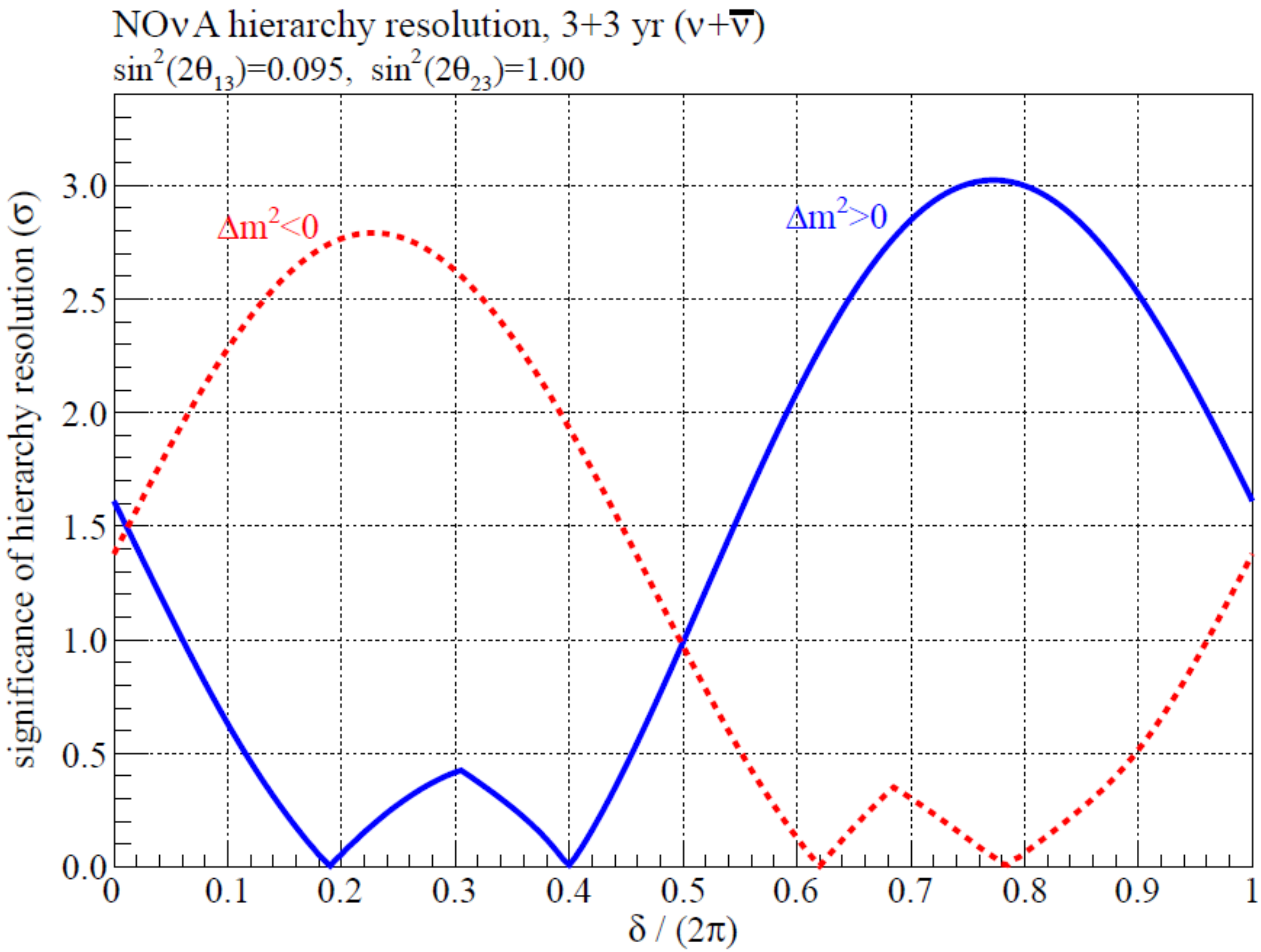
1 and 2 σ Contours for Starred Point



*In this kind of measurement we would determine that the mass hierarchy is **normal** with 3σ confidence and that*

$$\delta = \frac{3\pi}{2} \pm \frac{\pi}{4}$$

Mass Hierarchy Resolution



θ_{23} ambiguity

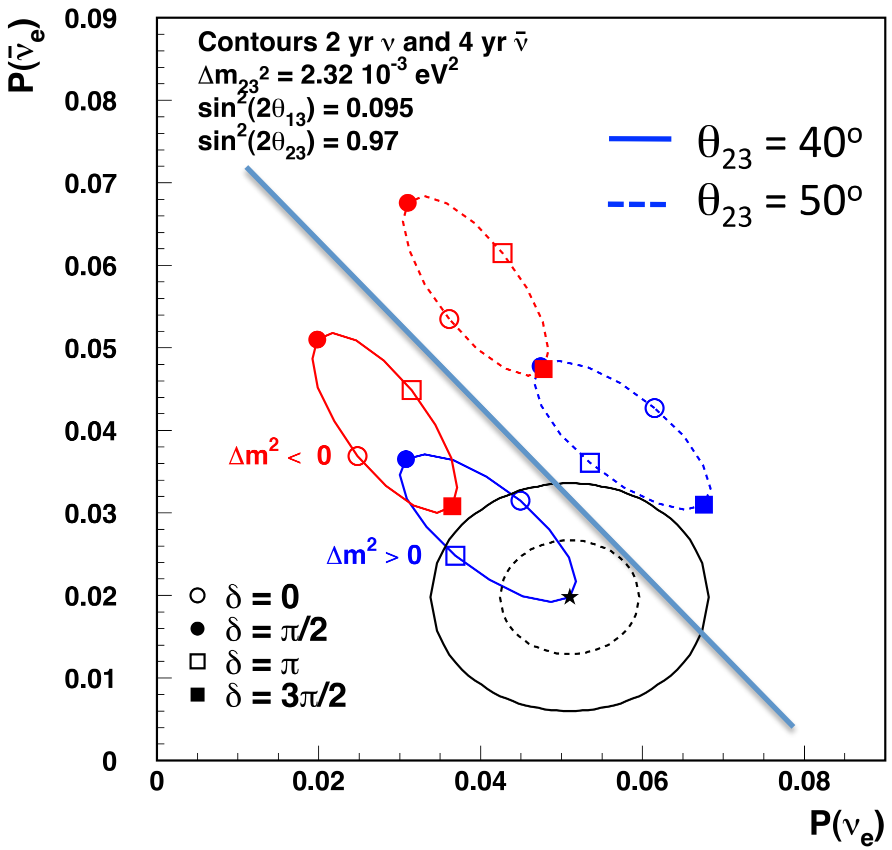
Currently there is an ambiguity in θ_{23} because atmospheric neutrino experiments measured ν_μ disappearance, which is sensitive to

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

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

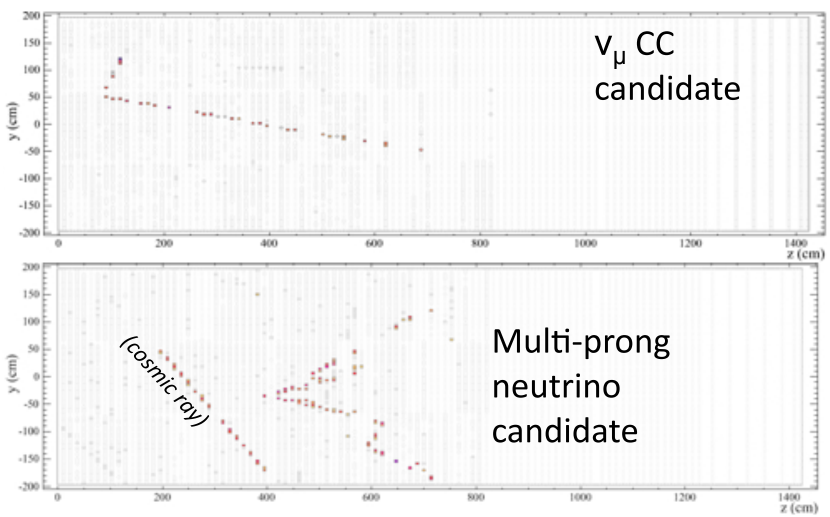
NOvA will additionally constrain the value of θ_{23} from ν_μ disappearance.

1 and 2 σ Contours for Starred Point



Prototype Near Detector on Surface

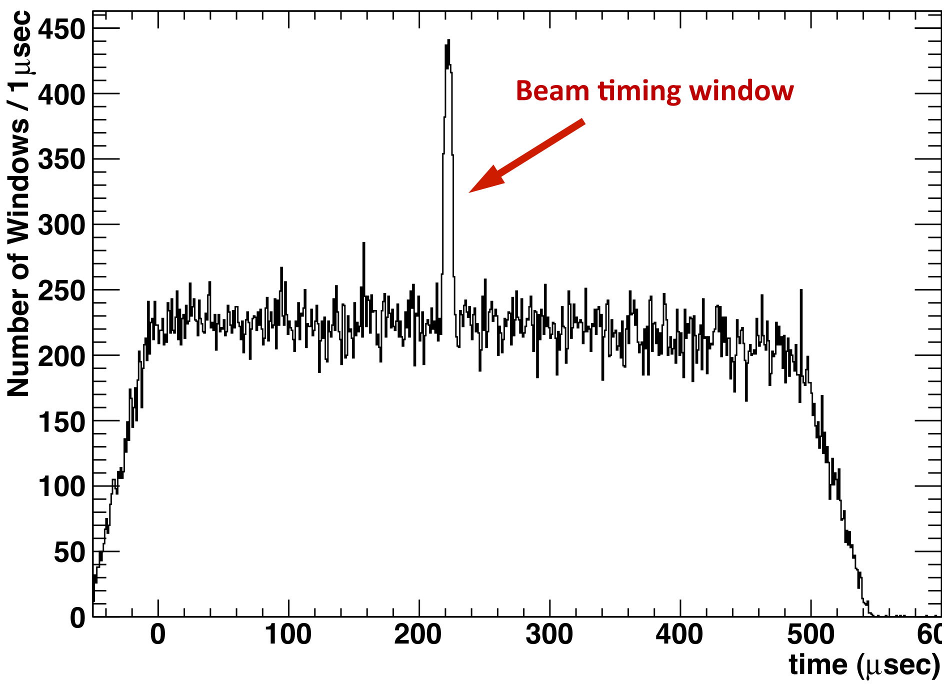
- Very similar design and scale to the actual NOvA Near Detector.
- Tested detector design, installation procedures, electronics, DAQ.
- Collected beam data from two neutrino beamlines to from December 2010 to April 30th 2012.
- Analyzing Data, performing calibrations.



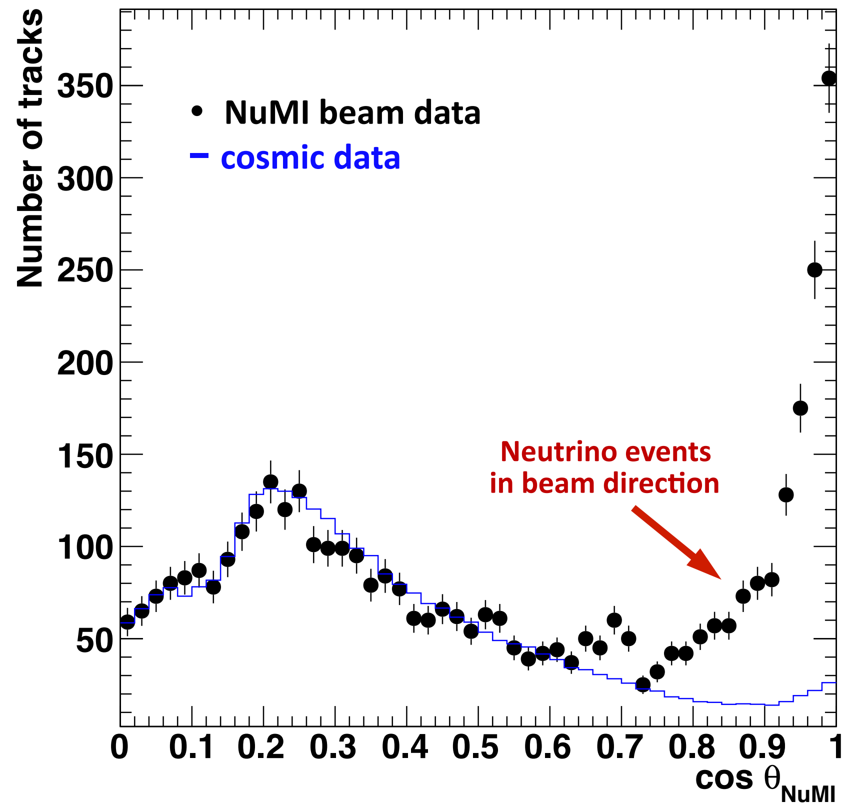
Prototype Near Detector on Surface

NuMI Neutrinos (MINOS, Minerva, Argoneut)

Track time in the beam trigger



Track direction

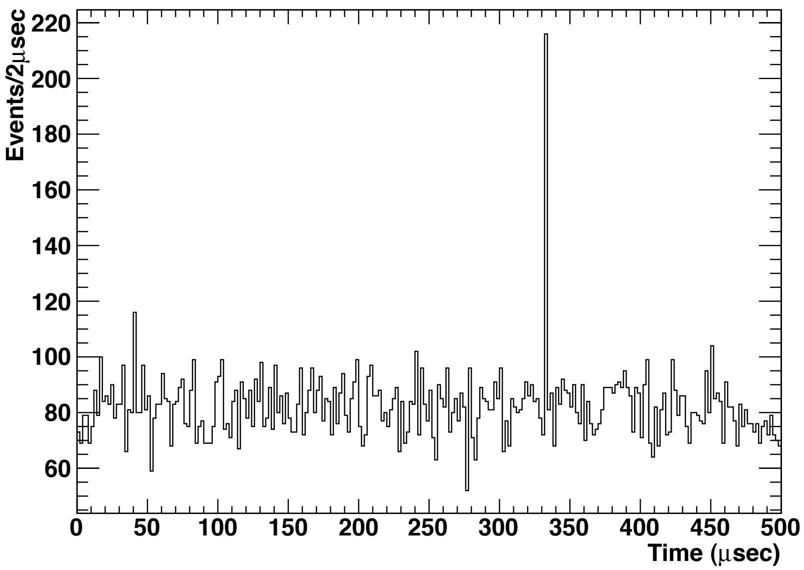


We do observe the neutrinos from the NuMI beamline

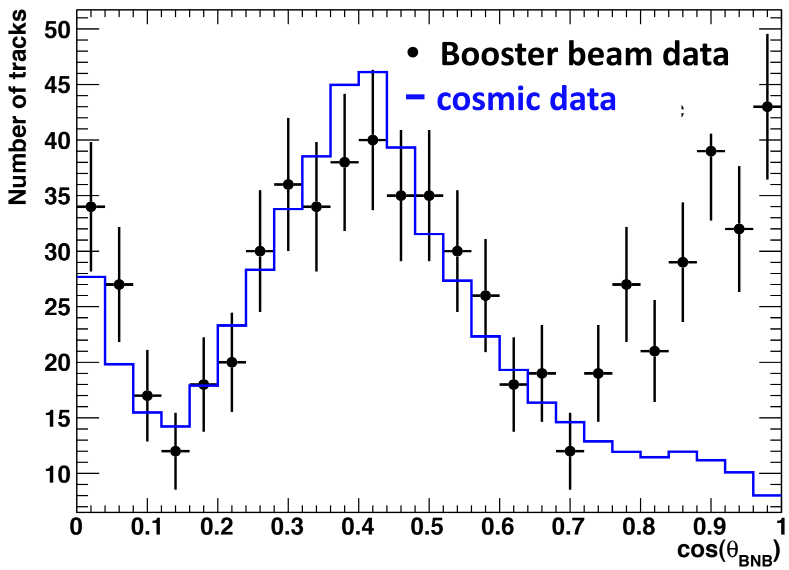
Prototype Near Detector on Surface

Booster Neutrinos (MiniBooNE, SciBooNE, MicroBooNE)

Track time in the beam trigger



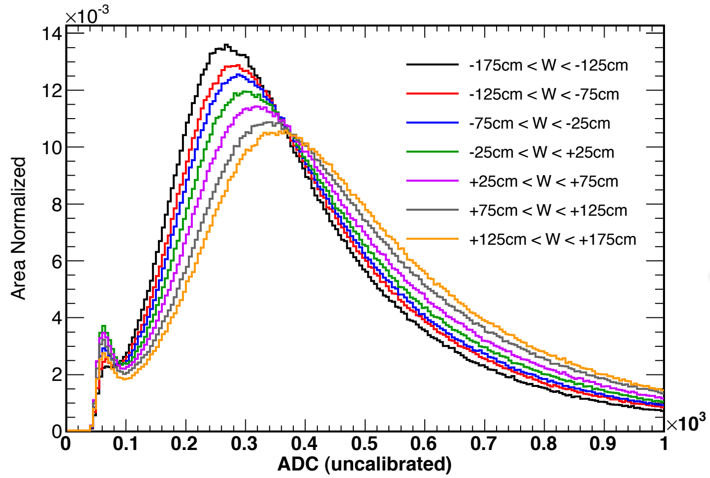
Track direction

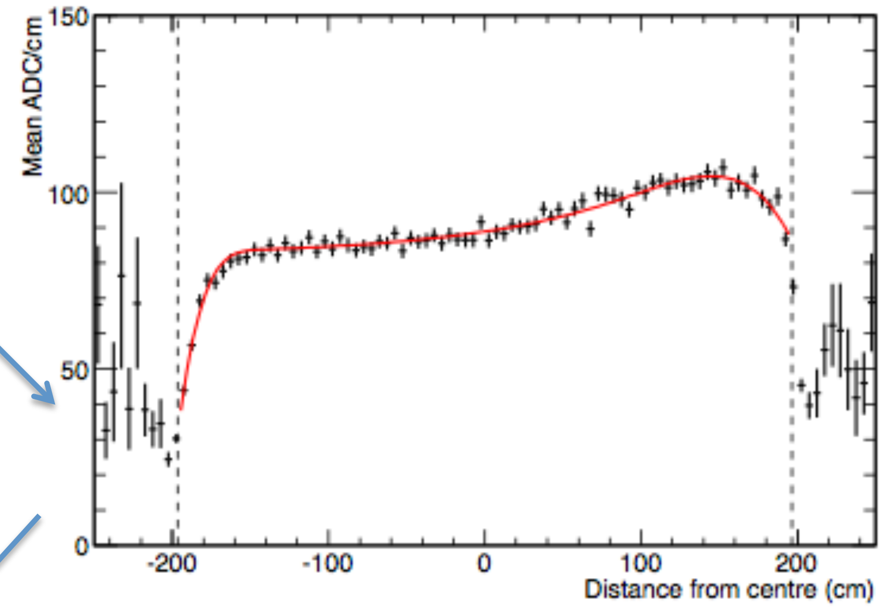


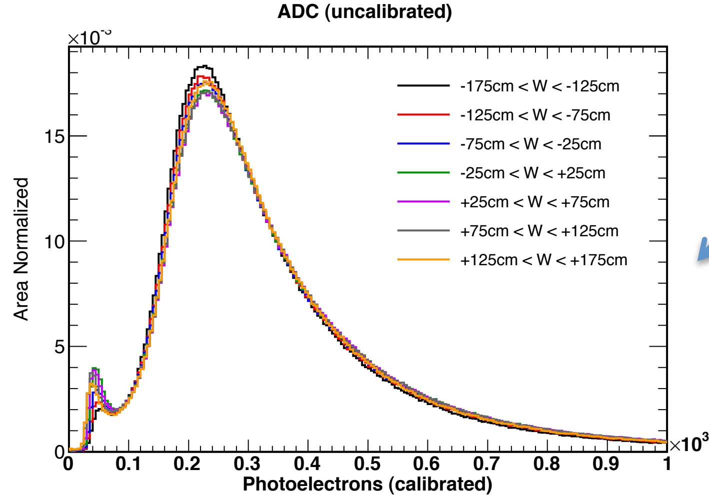
We do observe the neutrinos from the Booster beamline

Calibration. Attenuation.

Cosmic Data







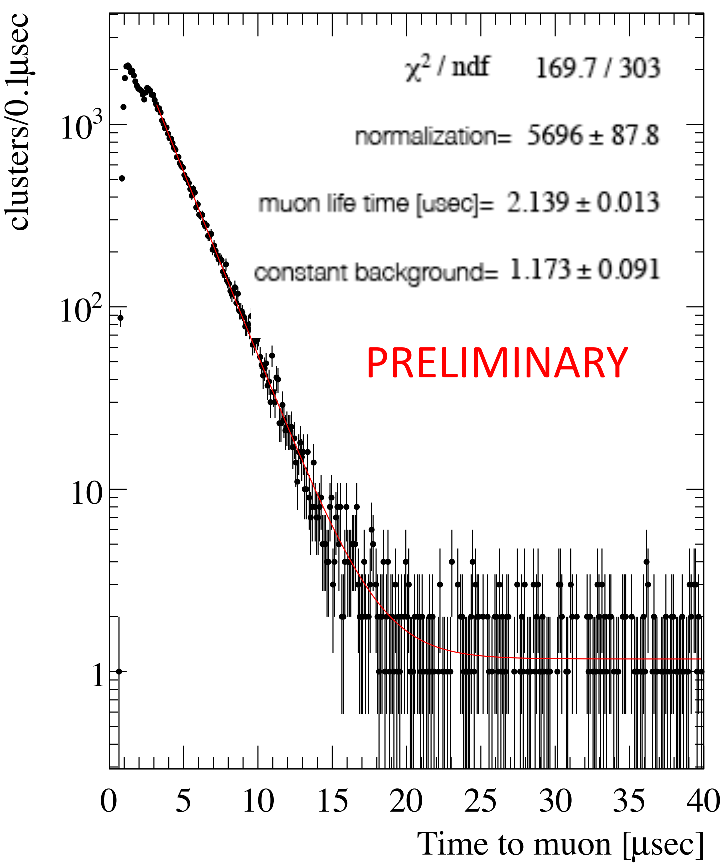
Top left: Path length-corrected muon response for different distances from fiber end for a single example cell

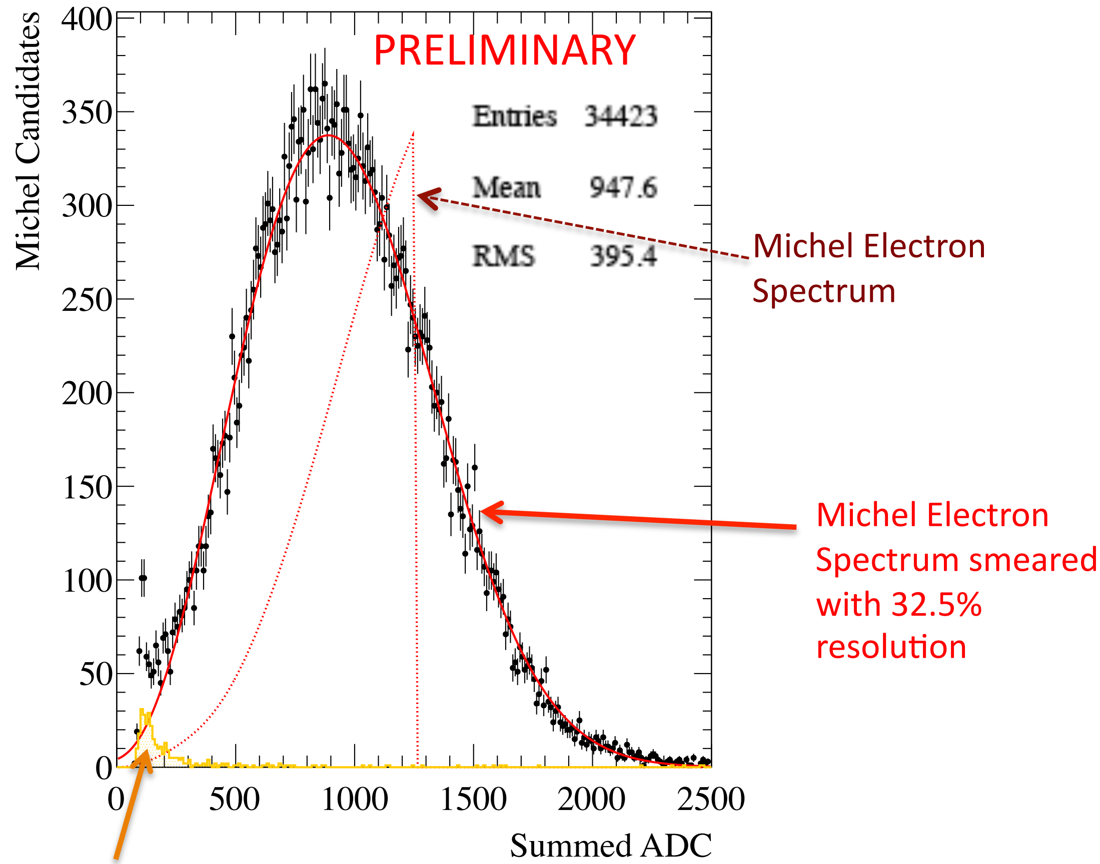
Above: Measured and fitted fiber attenuation for the example cell

Bottom left: Muon response after attenuation corrections

Calibration

Michel Electron Energy Spectrum





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

Far Detector Building is Complete

Inside the Hall

At the Opening Ceremony

Construction Status

Far Detector

- Block pivoter essentially complete
- Bookend, lifters, leak testers ready
- 1st block assembly to begin this month!

Block consists of 32 planes

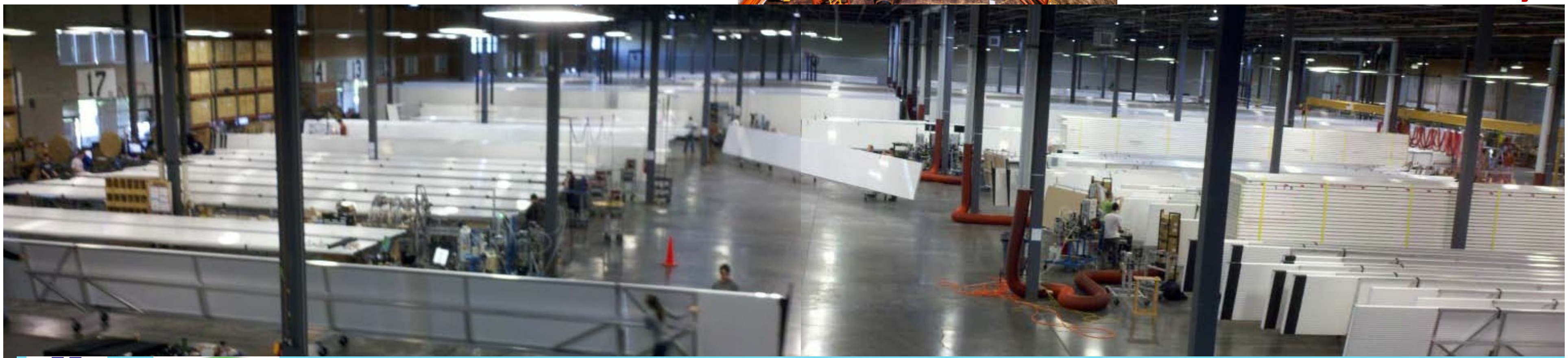
Block Pivoter

Module lifting fixture and adhesive dispenser

Near Detector

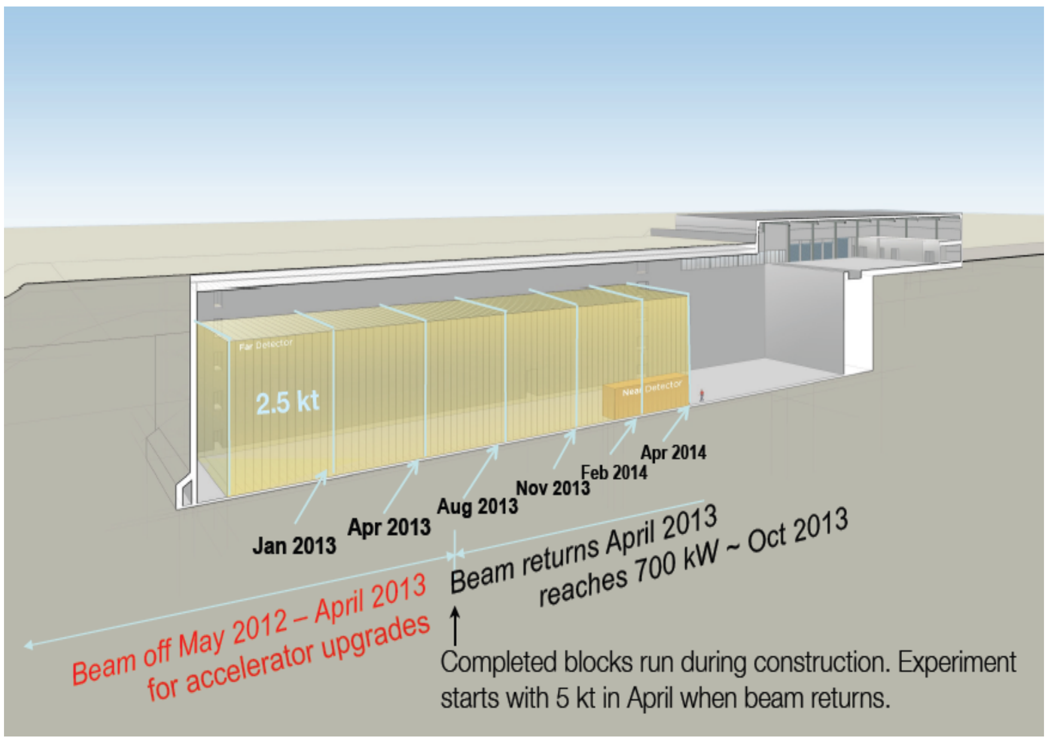
- Detector cavern excavation at Fermilab is being prepared

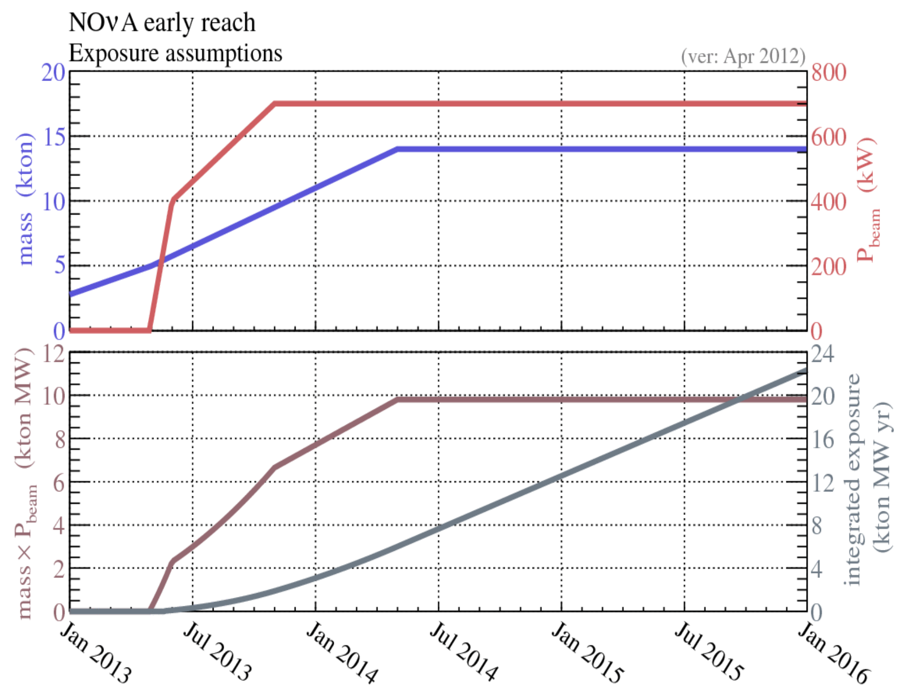
NOvA module factory



Construction Schedule

- NOvA will turn on April 2013 with 5 kton of Far detector in place and beam operating at about 400 kW.
- We will add detector mass at a rate of ~ 1 kton/month.
- Beam intensity will ramp up to 700 kW in approximately 6 months.





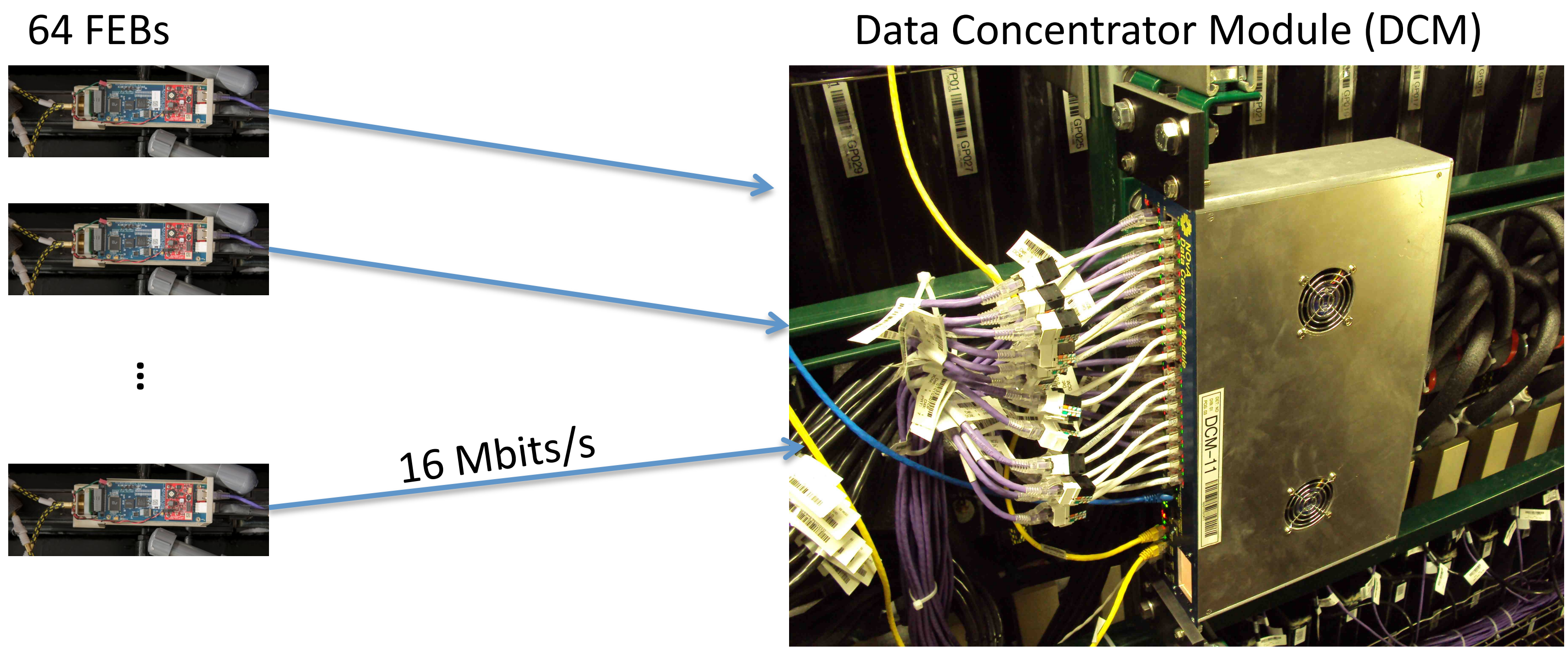
Conclusions

150+ Collaborators in 25 Institutions from 5 Countries

- NOvA has become the leading experiment at Fermilab
- Recent results from T2K and reactor neutrino experiments are very encouraging for the NOvA program.
- NOvA prototype detector has taken beam/cosmics data and has provided critical feedback to all aspects of the experiment.
- Far Detector construction is to begin this month so please … *Stay Tuned!*

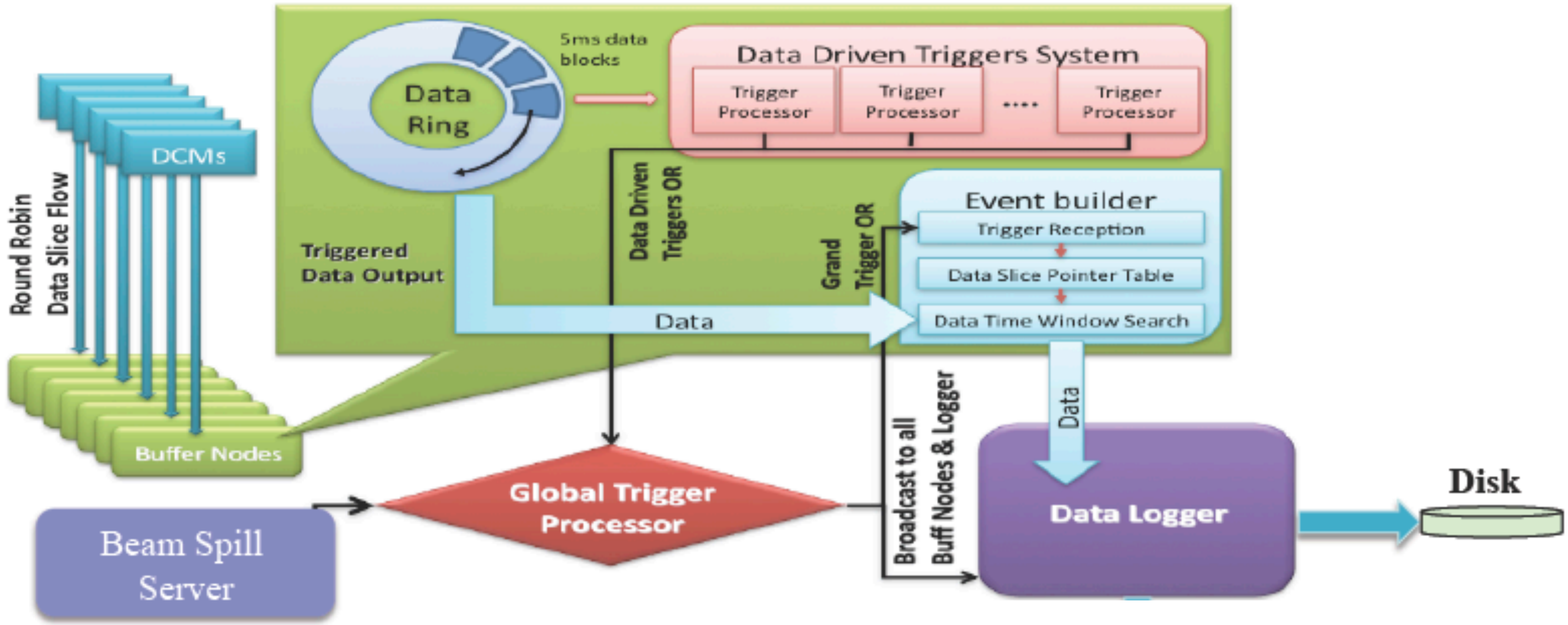
BACKUPS

Data Acquisition System

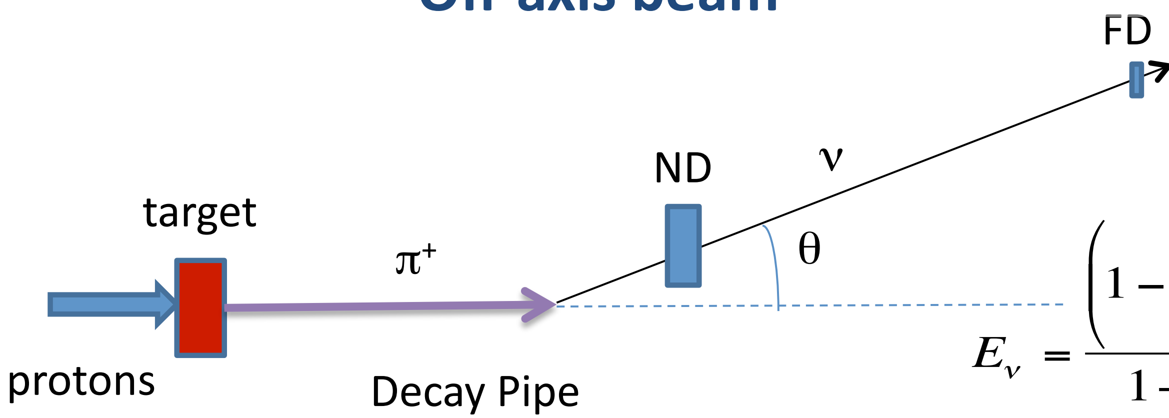


- 64 FEBs provide input to the Data Concentrator Module (DCM)
- DCM packetize the data and sends it through the Gigabit Ethernet to Buffer Nodes
- No data loss at this stage of the data transmission

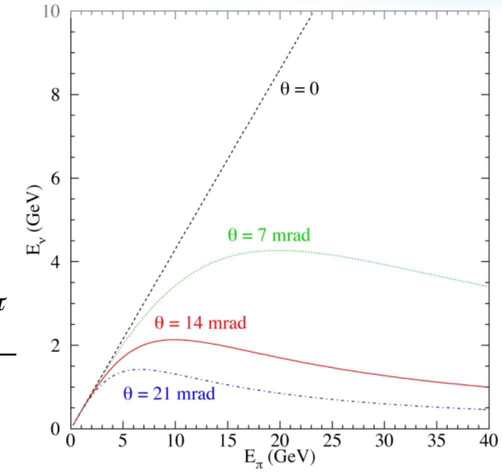
Data Acquisition System



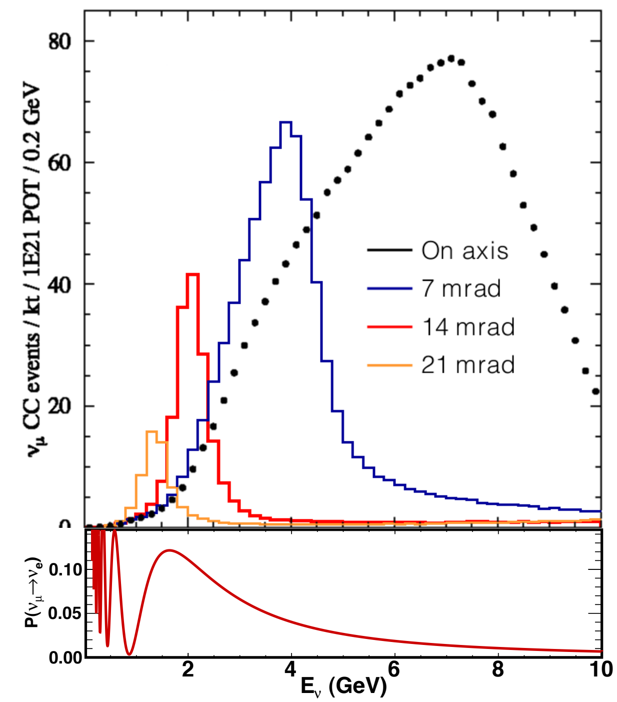
Off-axis beam



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



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



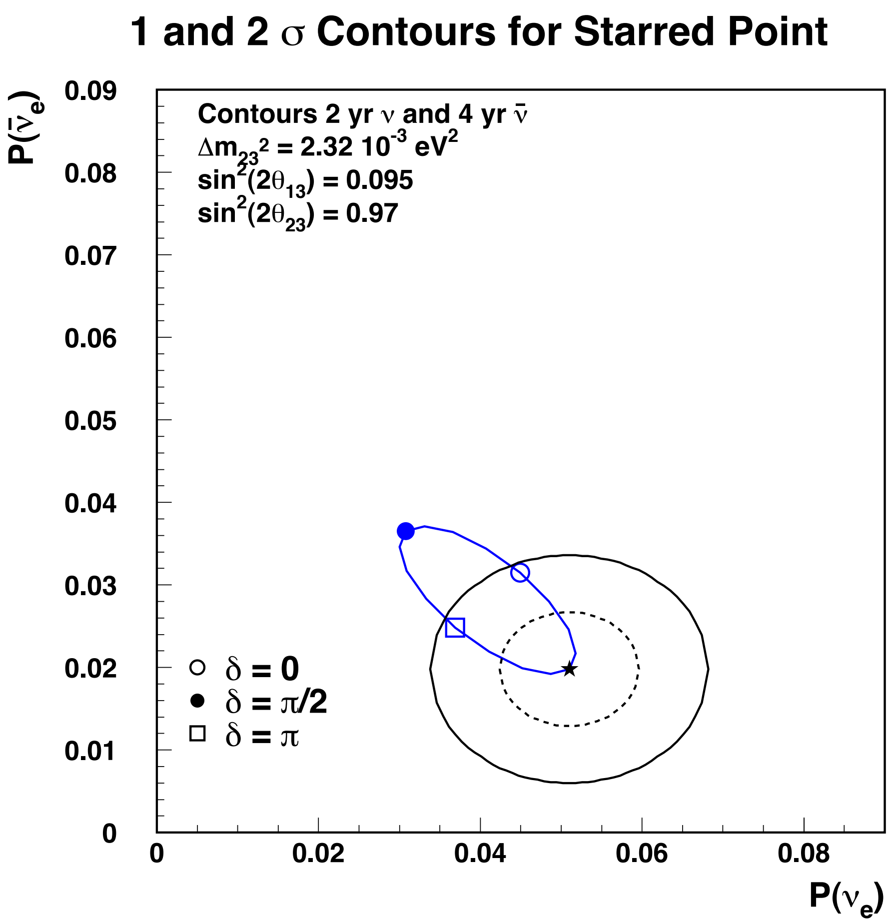
- **Enhanced 700 kW NuMI beamline (Currently 300 kW).**
- **Reduce cycle time from 2.2 to 1.3 seconds.**
- **Increased intensity/cycle with additional Booster batch.**
- **New horn and target.**
- **10μs beam pulse every 1.3 seconds.**
- **4.9e13 POT/pulse or 6e20 POT/year.**

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

Different values of δ_{CP} give different oscillation bi-probability

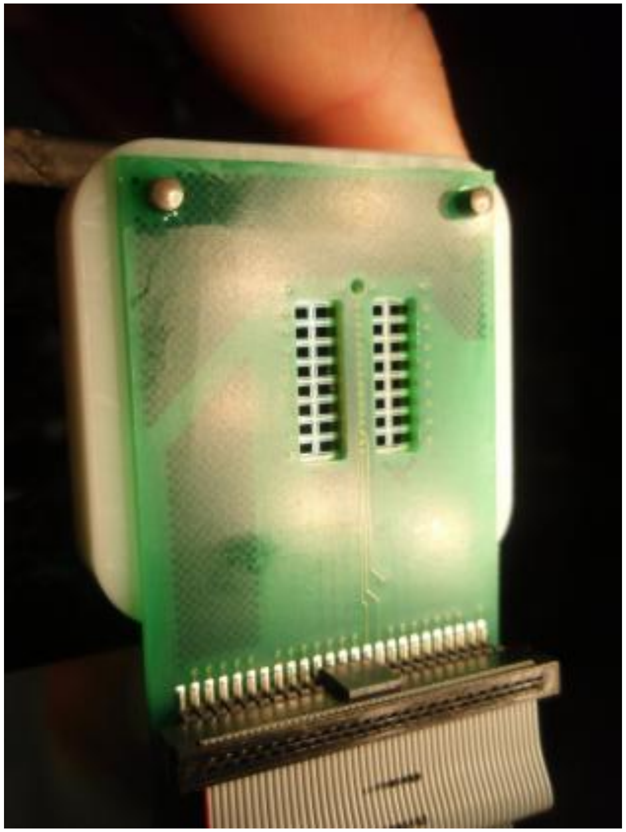
In this example, the measurement would lead roughly to:

$$\delta_{CP} = \frac{3\pi}{2} \pm \frac{\pi}{4}$$



Avalanche photo-diode (APD)

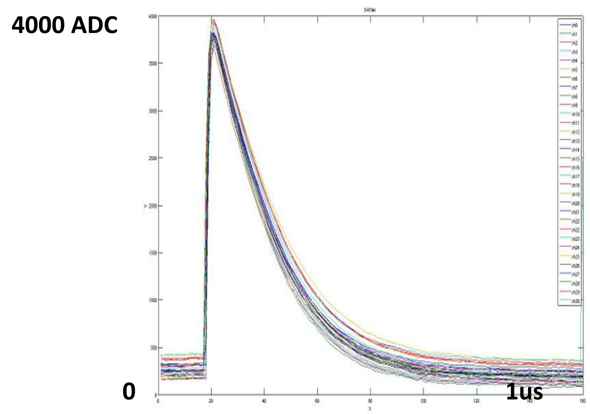
- ○ Relatively inexpensive (about $10 per channel)
- ○ 85% QE for 520 – 550 nm light.
- ○ Gain of 100 @ 375 volts.
- ○ Array of 32 pixels
- ○ Actively cooled to -15°C.
- ○ 11,150 APDs at the Far detector



Front-end-board (FEB)

○ Low noise ASIC amplifier is developed to maximize the sensitivity to small signals from the fiber.

ASIC signal output as a function of time



○ Analog-to-Digital converter samples each pixel with a frequency of 2 MHz (8 MHz at the Near Detector)

○ Field Programmable Gate Array preselects "hits" and sends the readout information to DAQ.

○ Thermo Electric Cooler Controller controls the amount of drive current to supply for a Thermo Electric Cooler installed on the APD module.

The large θ13 is extremely good for NOvA since it leads to large event rates in the far detector and enhancing early sensitivities.

The following sensitivities use our earlier analysis approaches but include the latest knowledge of θ13
Sin22θ13=0.095
Optimized for ~4% oscillation probability
10% uncertainty on backgrounds
41% (ν) and 48% (anti-ν) signal efficiency

Beam	Signal	NC Bkg	ν_μ CC	ν_e CC	Total Bkg
ν (3 yr)	72.6	20.8	5.2	8.4	34.5
$\bar{\nu}$ (3 yr)	33.8	10.6	0.7	5.0	16.3

Estimated numbers based on:
15 kton, 18 x 1020 POT (3 years each neutrino-mode running)
No solar-atmospheric terms and no matter effects