Neutrino oscillation physics at NOvA experiment

Vladimir Kravtsov, Southern Methodist U
on behalf of the NOvA collaboration

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NOvA (NuMI Off-Axis ν_e Appearance) Experiment

Second generation long baseline off-axis neutrino experiment

Ash River, MN

Minnesota

810 km

Wisconsin

Iowa

Indiana

Missouri

Fermilab

810 km long baseline.

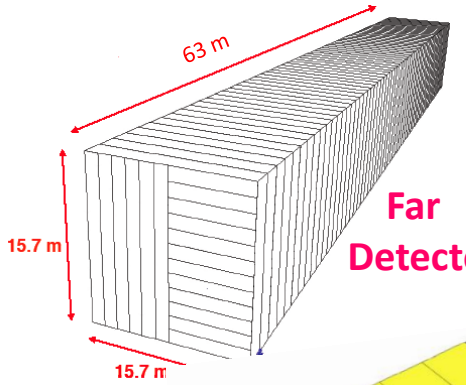
700 kW NuMI beam.

2 GeV peak energy.

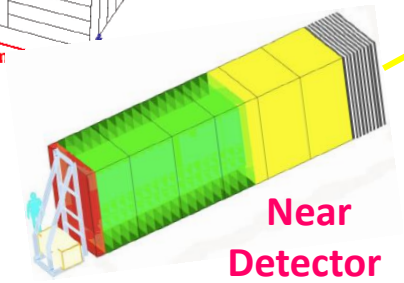
Far detector in Ash River, MN.

Near detector 1 km from target.

14 mrad off-axis beam.



Far Detector



Near Detector

Main Injector Ring

NOvA Collaboration

184 members from 36 Institutes in 7 countries

Main Physics Goals

NOvA experiment is designed to measure 4 oscillation channels:

$$\nu_\mu \to \nu_e,\ \bar{\nu}_\mu \to \bar{\nu}_e,\ \nu_\mu \to \nu_\mu,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$$

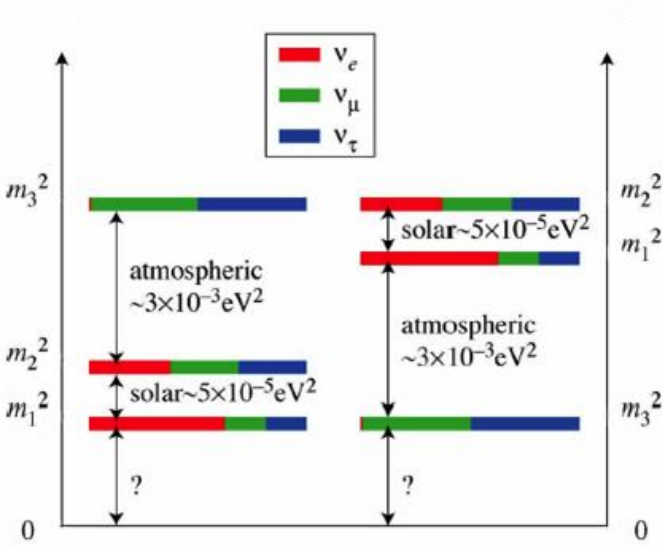
- **Measurement of mixing angle θ_{13} by ν_e appearance**

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27\Delta m^2_{31} L / E_\nu\right)$$ - Leading term

- **Determination of neutrino mass hierarchy (normal or inverted)**

- **Search for CP violation in neutrino sector**

- **Determination of θ_{23} octant**



- **Precise measurement θ_{23}, $|\Delta m_{32}^2|$ by ν_μ disappearance**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin\left(1.27\Delta m^2_{32} L / E_\nu\right)$$ - Leading term

NOvA Early ν_e Appearance Reach

NOvA will start with neutrino running

- 5σ observation of $\nu_\mu \rightarrow \nu_e$ in first year if **NH**.
  (even with partial detector and beam commissioning!)
- Switch to antineutrino running any time as needed.
- Nominal run plan:
  3 yrs. in ν + 3 yrs. in $\bar{\nu}$ modes at 6x10^{20} POT/year.

NOvA sensitivities were recalculated including **new θ_{13}** knowledge:

- $sin^2(2\theta_{13})$ = 0.095
- $sin^2(2\theta_{23})$ = 1.00
- Signal efficiency: 45%
- NC fake rate: 1%

Event counts for $\nu_\mu \rightarrow \nu_e$ analysis (3yr +3yr)

Beam	ν_μ CC	ν_e CC	*NC*	BG tot.	Signal
ν	19	5	8	32	68
$\bar{\nu}$	10	< 1	5	15	32

NOvA Measurement

NOvA will measure:

$P(\nu_\mu \rightarrow \nu_e)$ at 2 GeV

$P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$ at 2 GeV

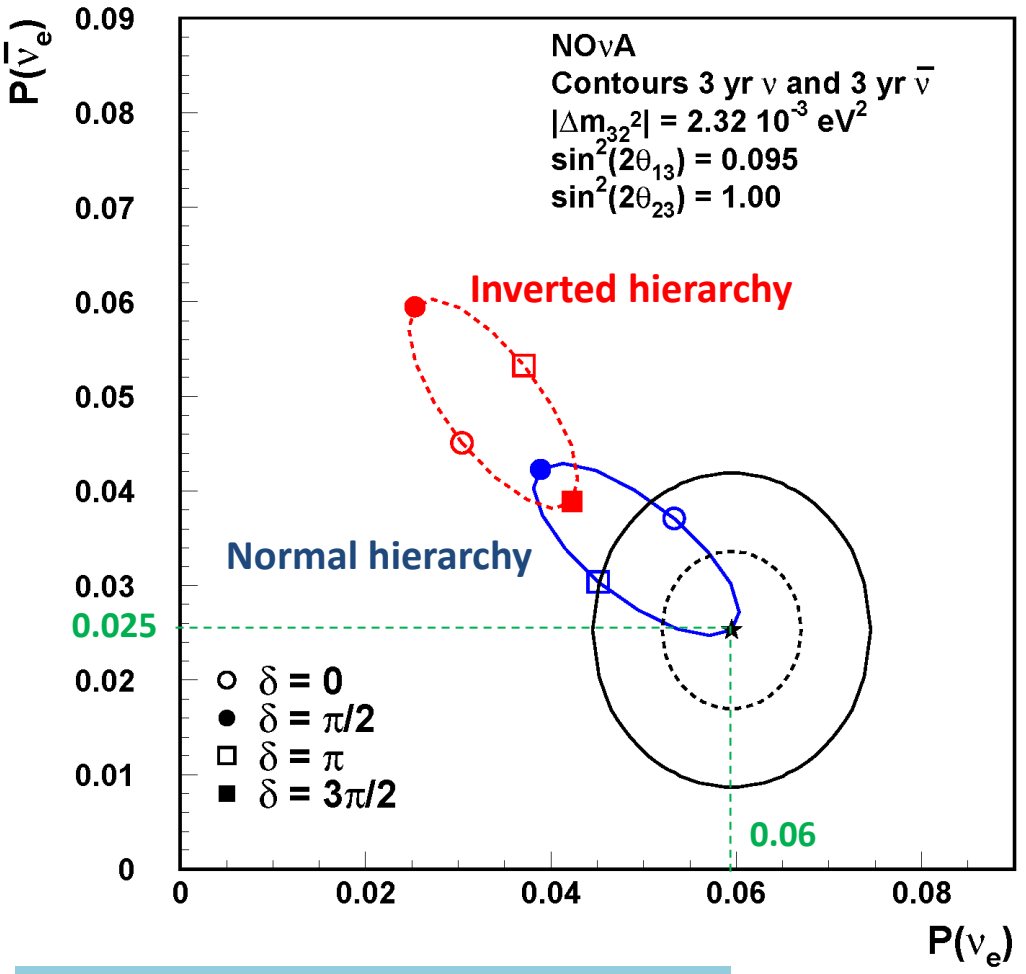
These probabilities depend *in different ways* on

- CP phase δ
- $sign(\Delta m^2)$

NOvA strategy is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$.

Starred point is an example of NOvA measurement with 1σ and 2σ contours.

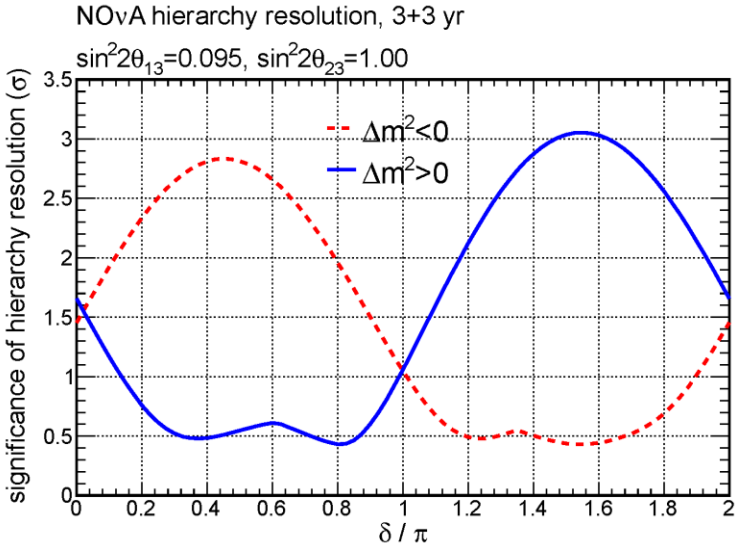
Here, all IH scenarios are excluded at >2σ level

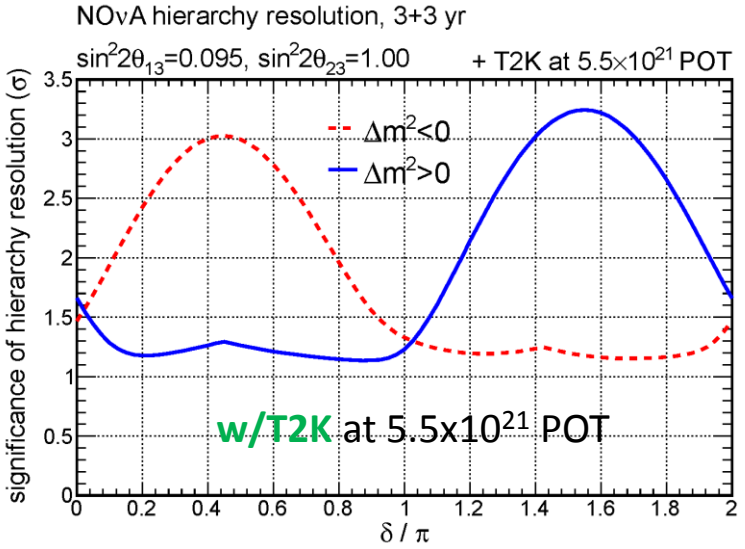


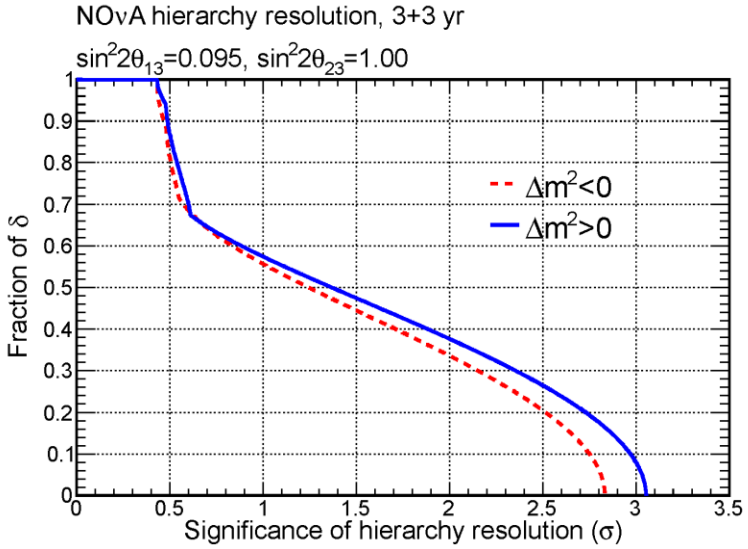
Large θ_{13} is good news for NOvA as it reduces the overlap between bi-probability ellipses.

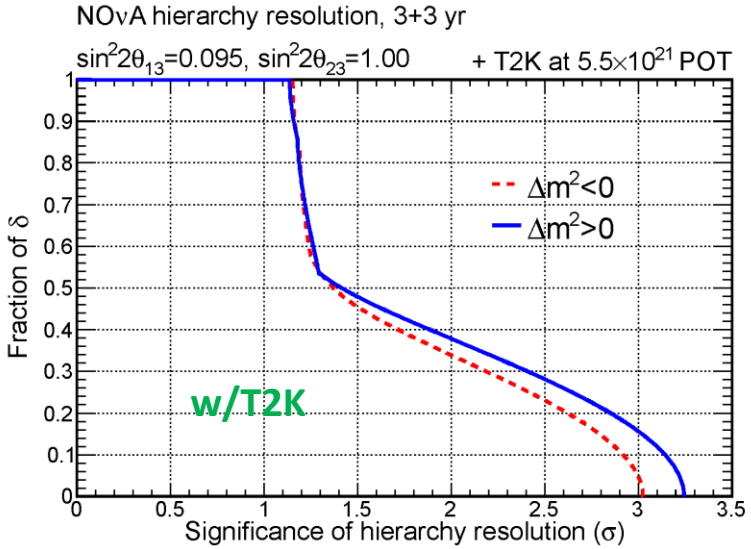
Resolving the Mass Hierarchy

Significance of the Mass Ordering Resolution.





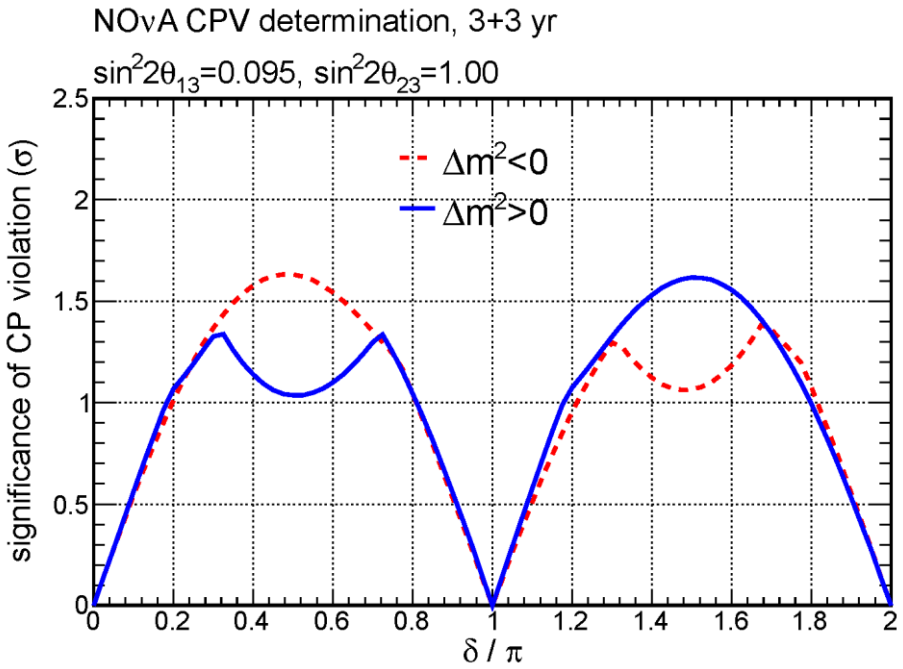


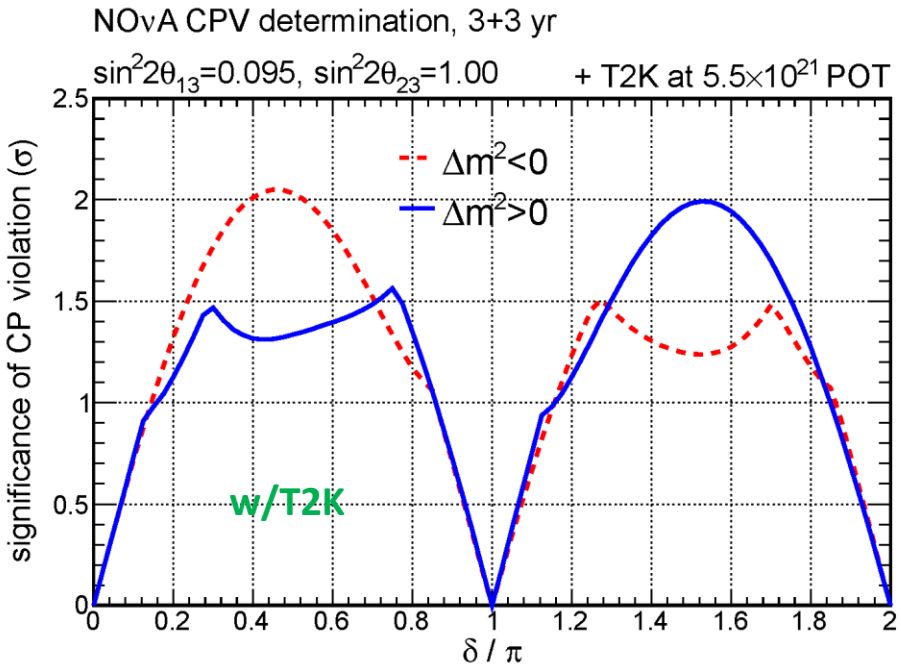


δ range included for given significance of hierarchy determination (NH case)

CPV determination

Significance with which NOvA can establish CP violation.





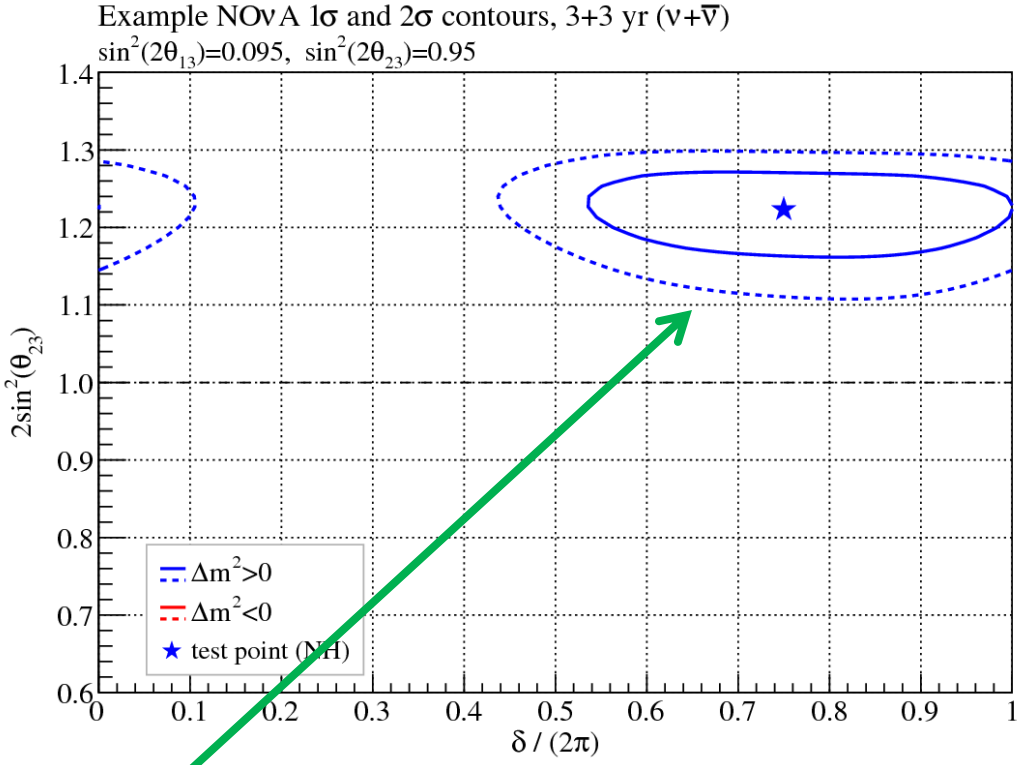
The significance goes to zero at $\delta = 0$ and $\delta = \pi$ since there is no CP violation at those points. The dips in the peaks occur because the mass ordering has not been resolved.

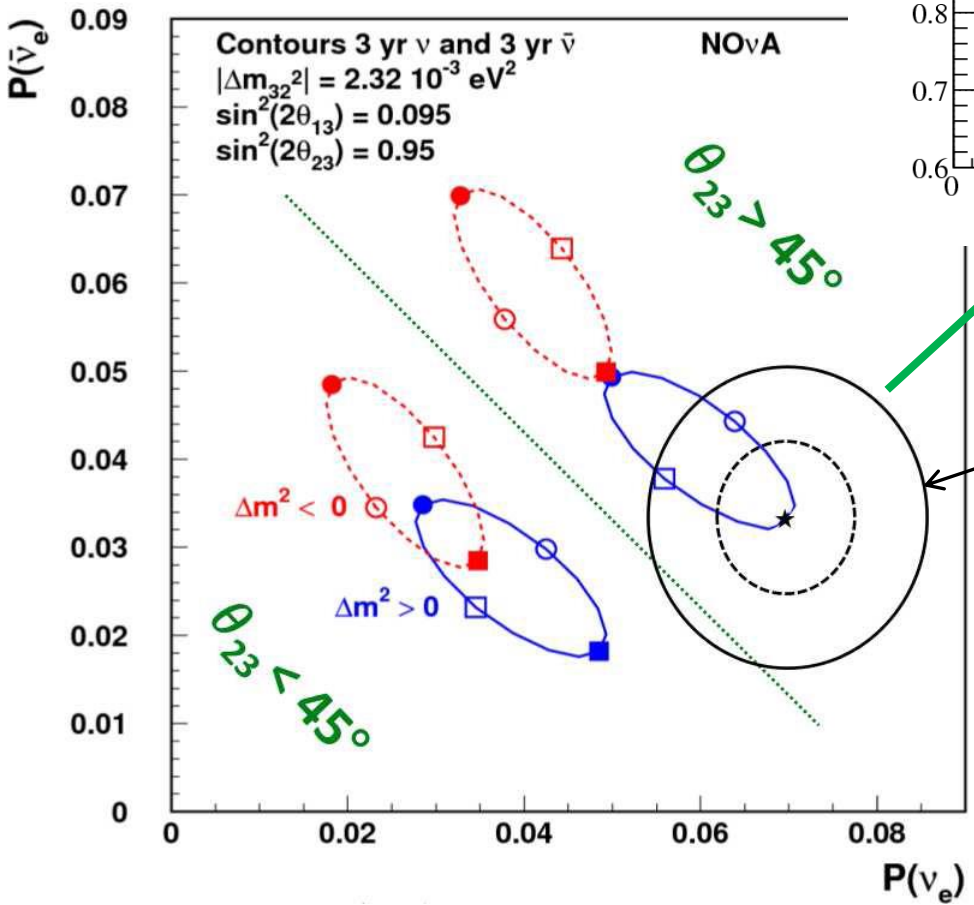
The CPV significance in the best-case scenario is 1.6σ without T2K and 2σ with T2K data.

θ_{23} Octant Sensitivity

$$P(\nu_e) \propto sin^2(\theta_{23})\, sin^2(2\theta_{13})$$

If θ_{23} is not maximal,
is it bigger or smaller 45°?

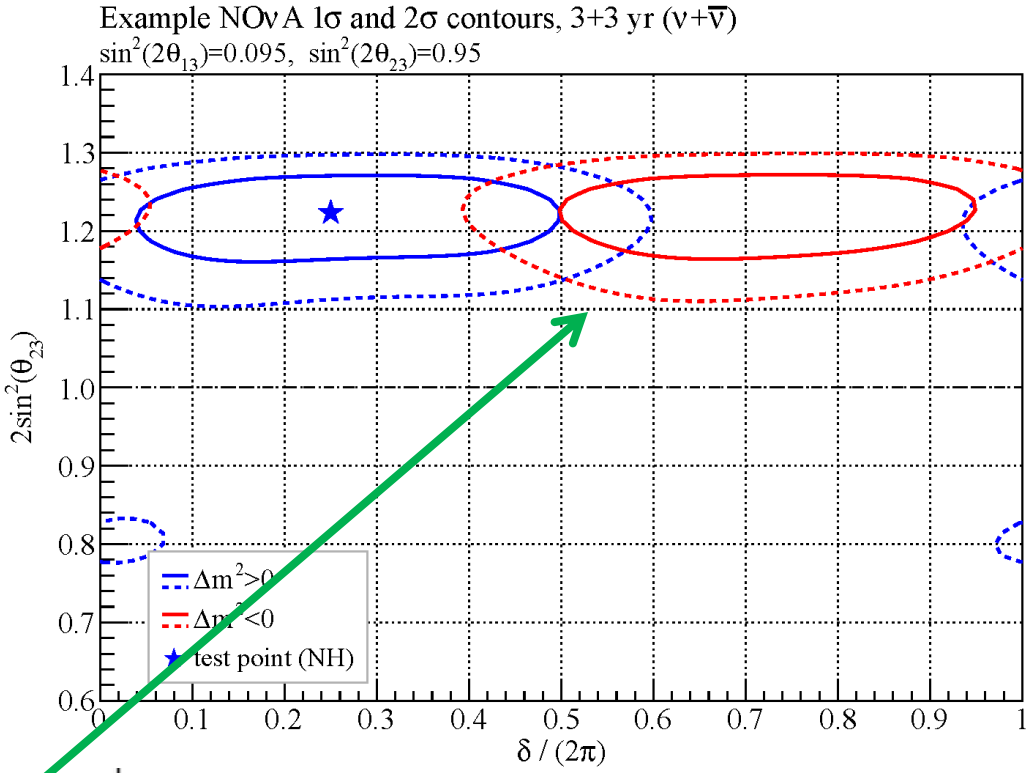




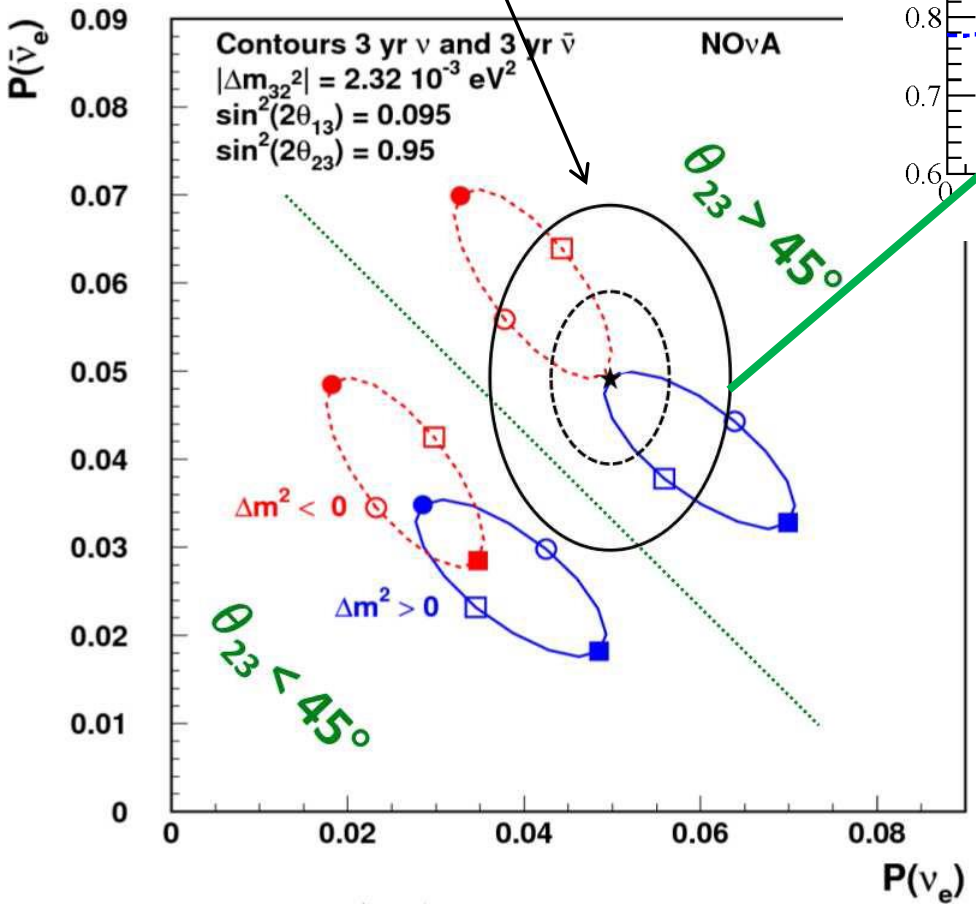
Example of starred point

We determine *hierarchy*, θ_{23} *octant* and rule out half of δ_{CP} space at 2σ.

θ_{23} Octant Sensitivity

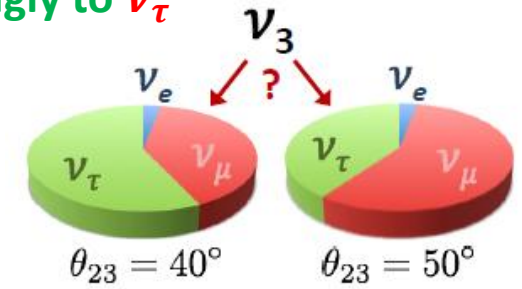


Example of starred point



In a degenerate case *hierarchy* and δ information are coupled, θ_{23} *octant* is not.

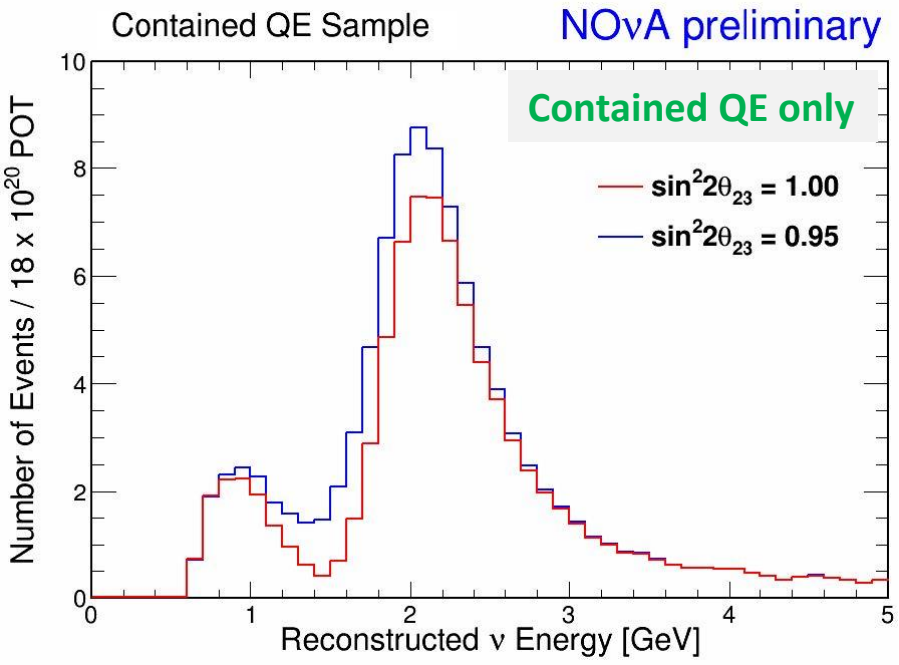
$\theta_{23} < 45°$ implies that ν_3 couples more strongly to ν_τ than to ν_μ

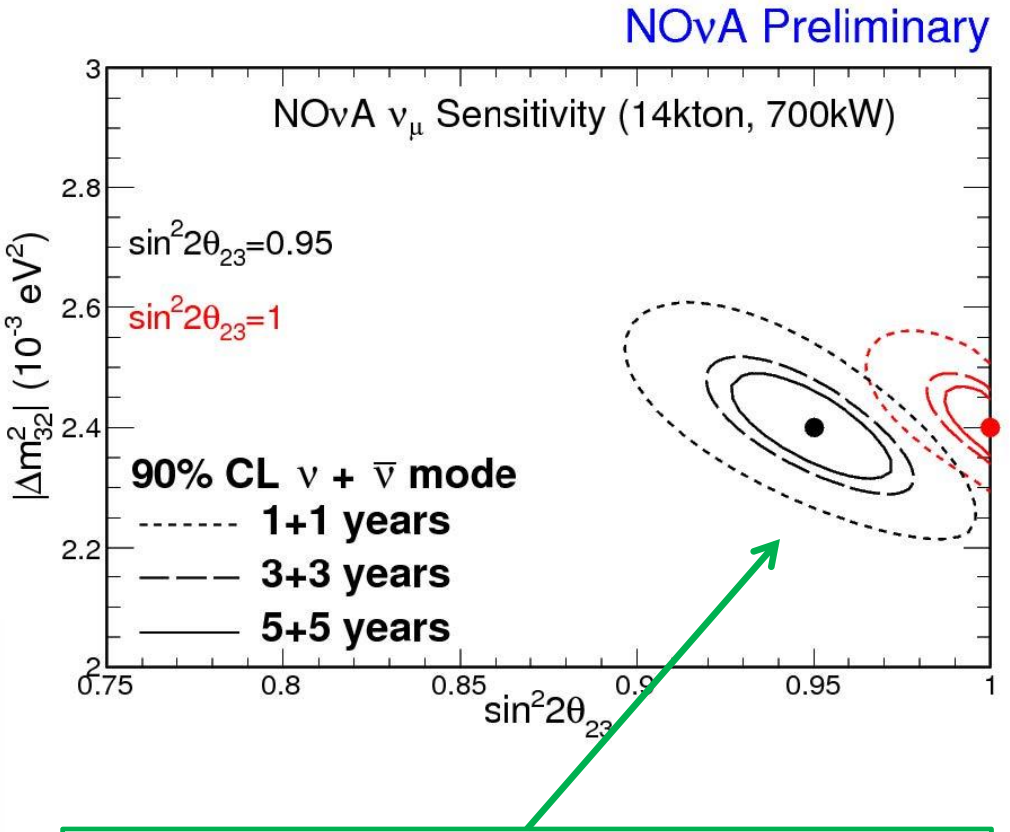


θ_{23} Sensitivity

The disappearance of ν_μ CC events measures $sin^2(2\theta_{23})$

- ✓ **4% average energy resolution for the QE events**
- ✓ **Very low background**

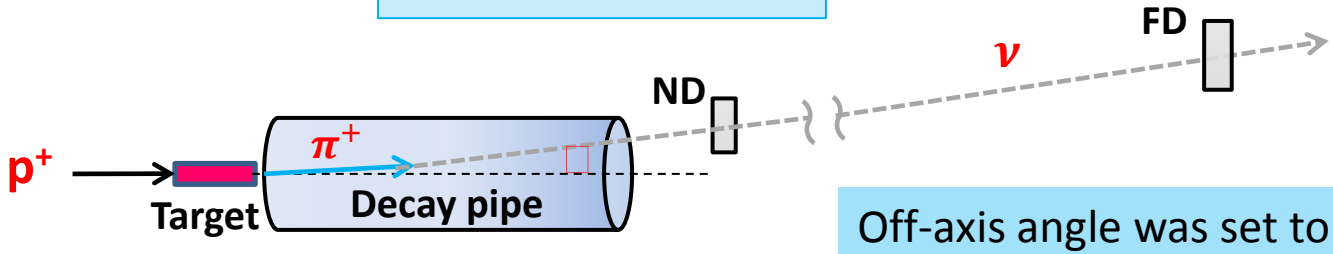




Combined analysis for three data samples:

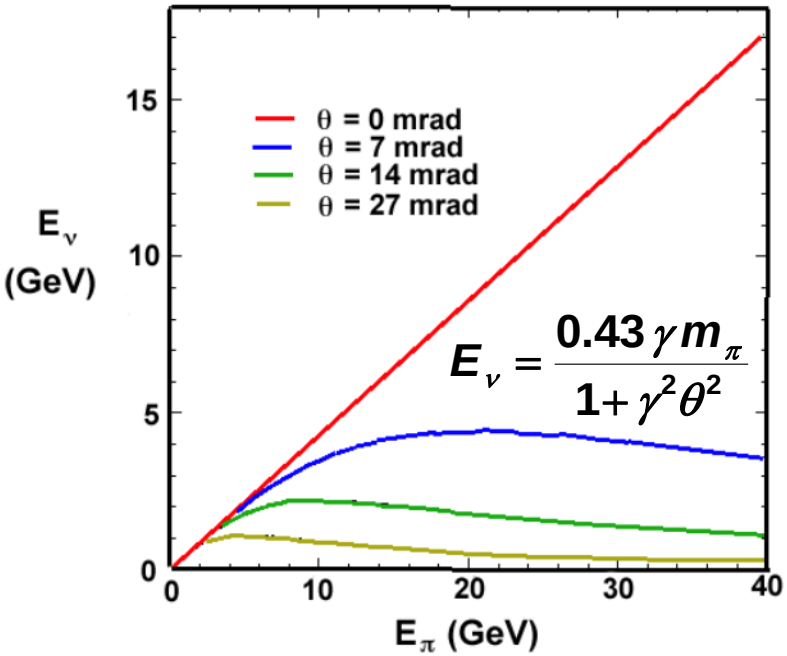
- Contained QE
- Contained non-QE CC
- Uncontained CC

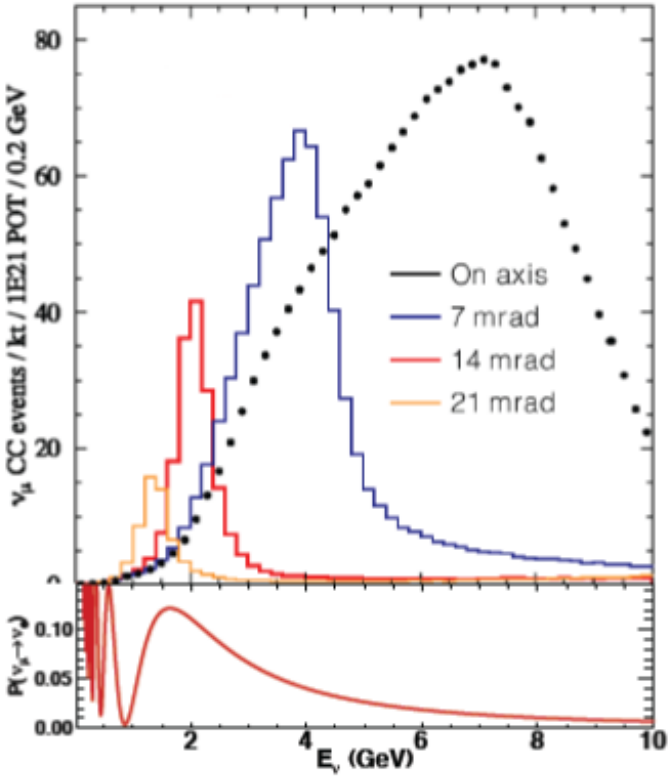
Off-Axis Beam



Off-axis angle was set to 14 mrad near an oscillation maximum

Off-axis concept was first proposed for the experiment E-889 at the BNL



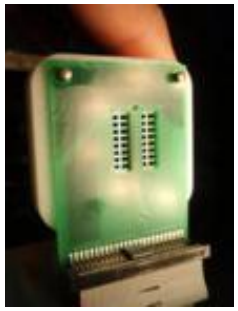


BNL report 52459, April 1995.

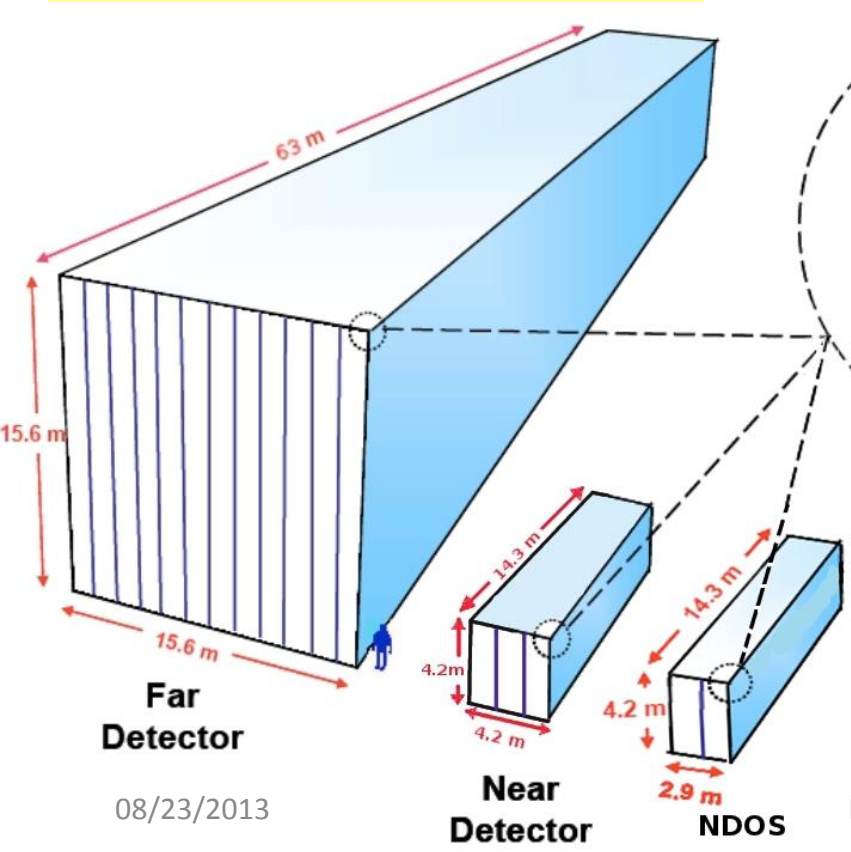
Narrow ν spectrum reduces the background in electron neutrino measurement.

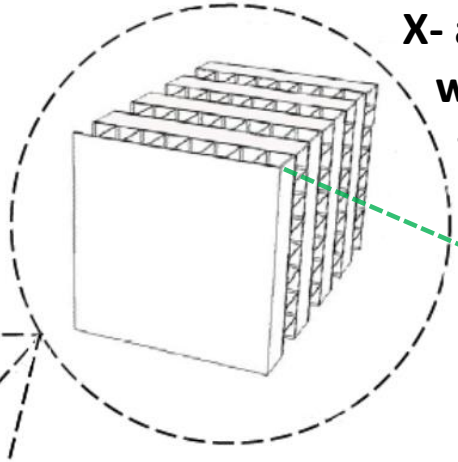
NOvA Detectors

- 14 kton Far Detector
  896 planes
  ~344,000 channels
- 300 ton Near Detector
  192 planes
  ~18,000 channels
- 200 ton FD prototype

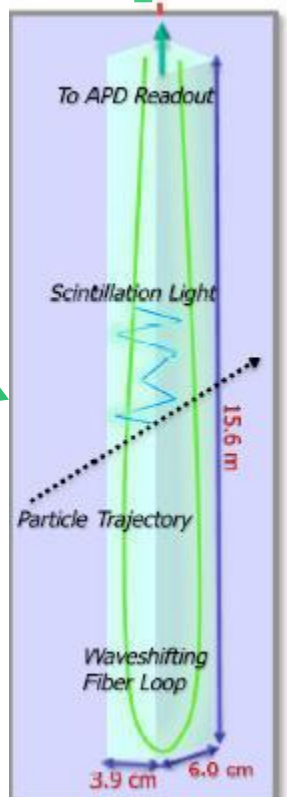


32-pixel APD





X- and Y-planes with 384 cells for FD and 96 cells for ND

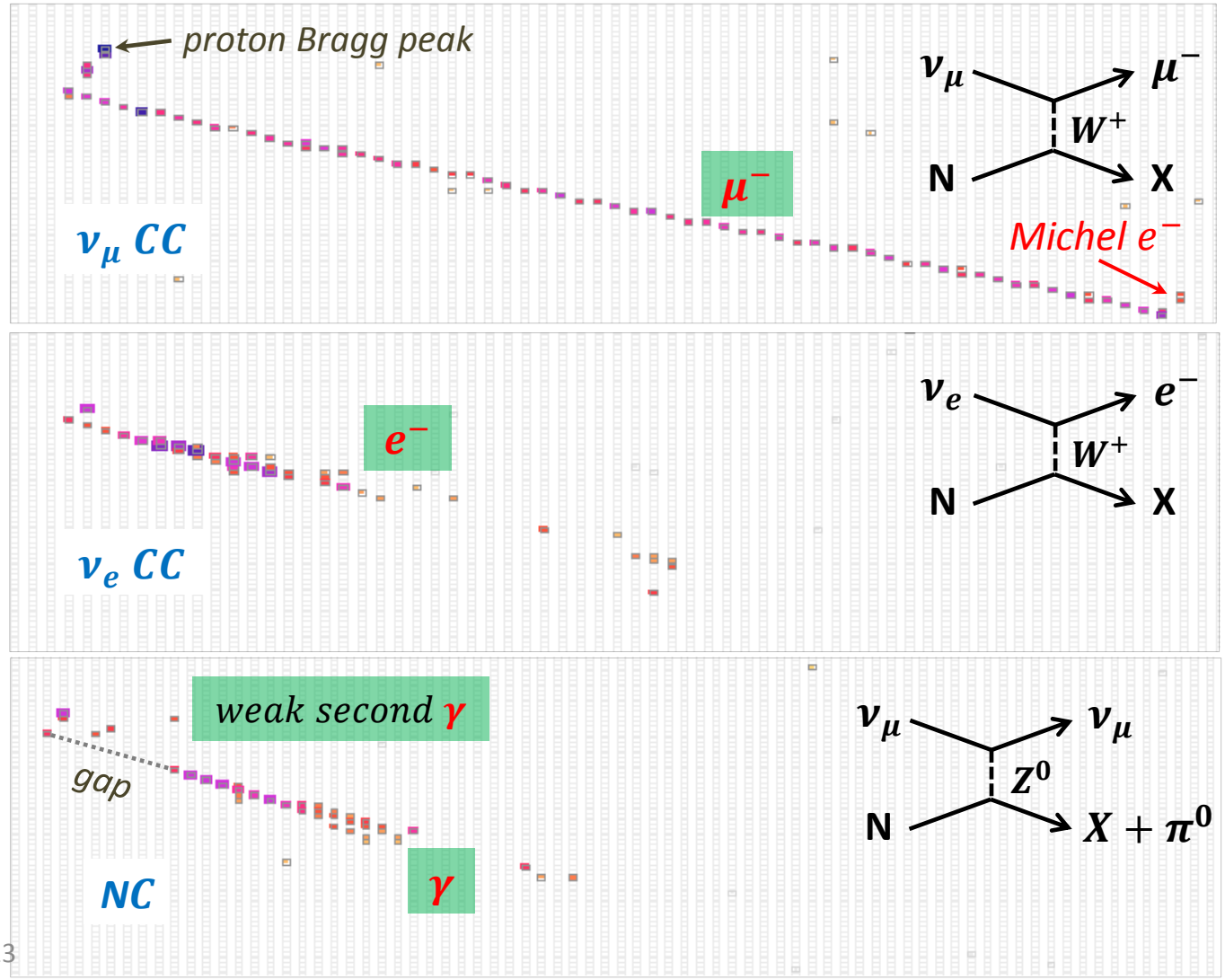


4 x 6 cm cell

- Extruded PVC cells are filled with scintillating mineral oil
- Scintillator light is collected by WLS to 32-pixel APD

Topology of Neutrino Events (MC Simulation)

NOvA detectors are optimized for detection of ν_e **CC** interaction.
Excellent granularity of detectors: 1 plane $\sim 0.17X_0$, $R_M = 11cm$

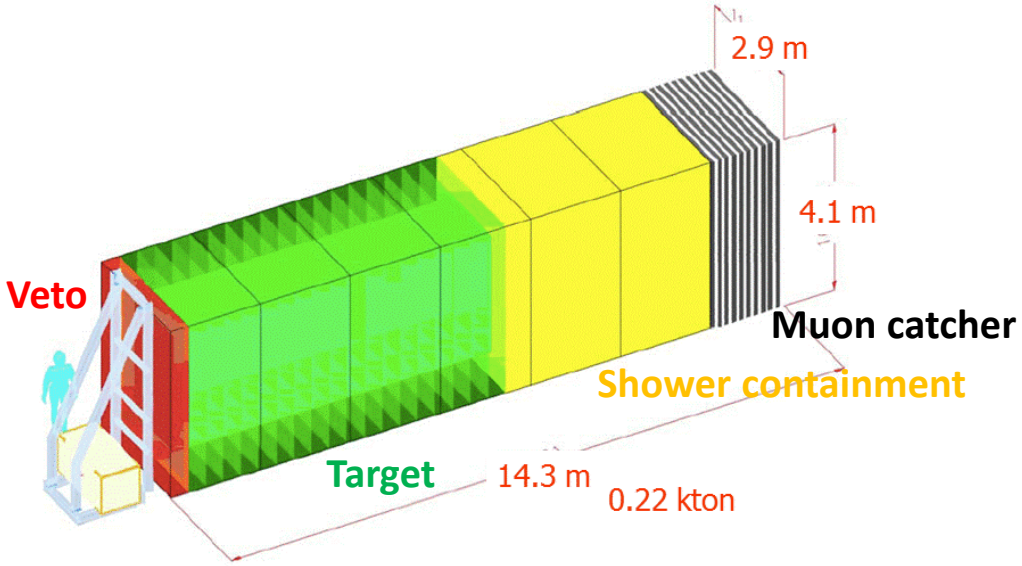


Prototype of Near Detector (NDOS)

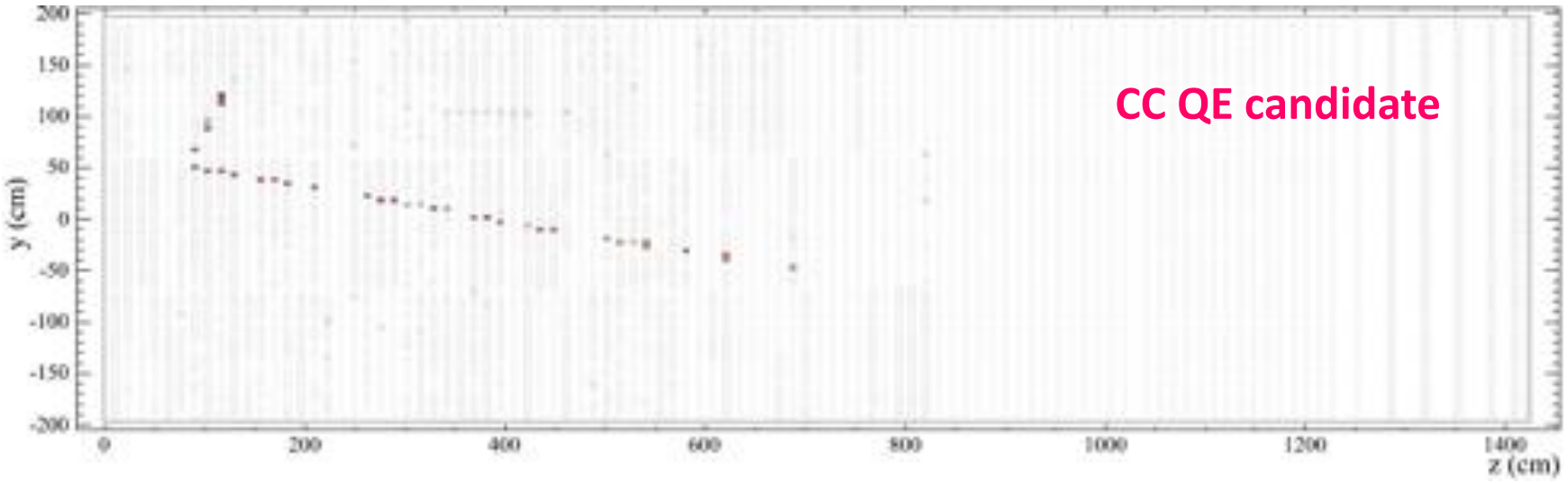
NDOS (Near Detector On Surface) is positioned 100m above the NuMI and Booster neutrino beams

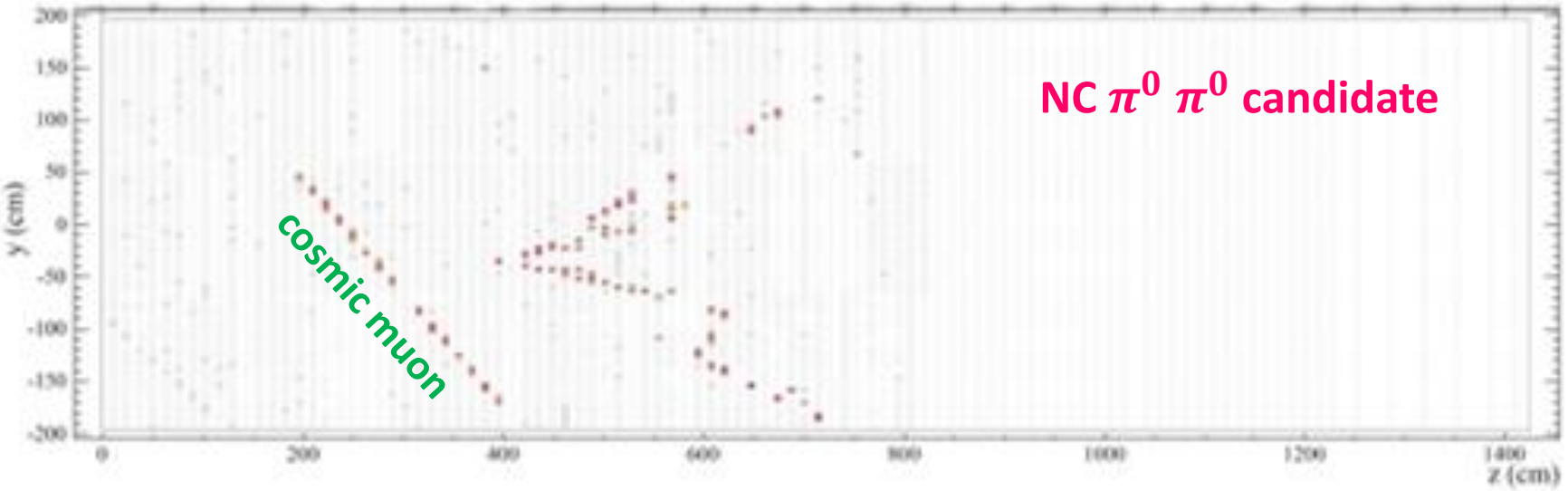
Main goals to build NDOS:

- Test detector design before near and far detectors production.
- Develop DAQ system.
- Detector calibration procedure development.
- Development of simulation and reconstruction software using real data.



NDOS Neutrino Event Candidates

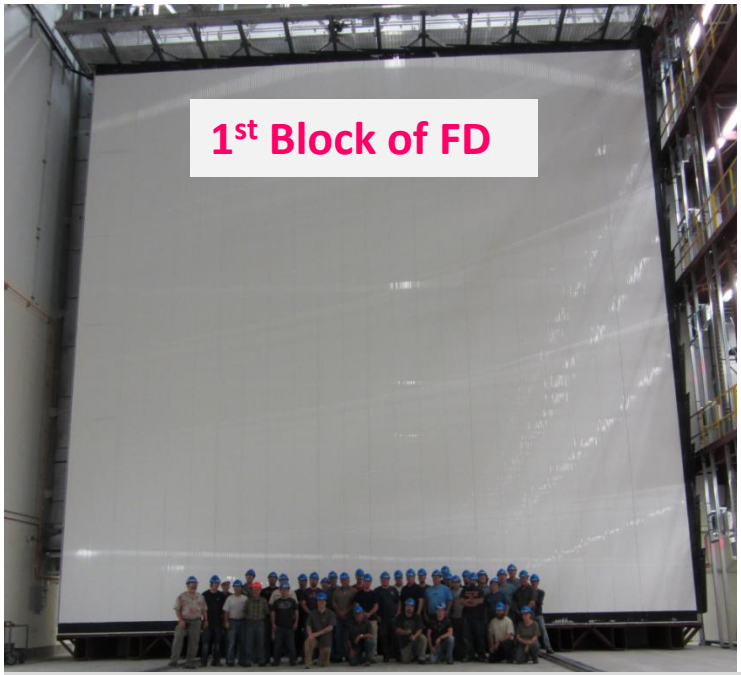




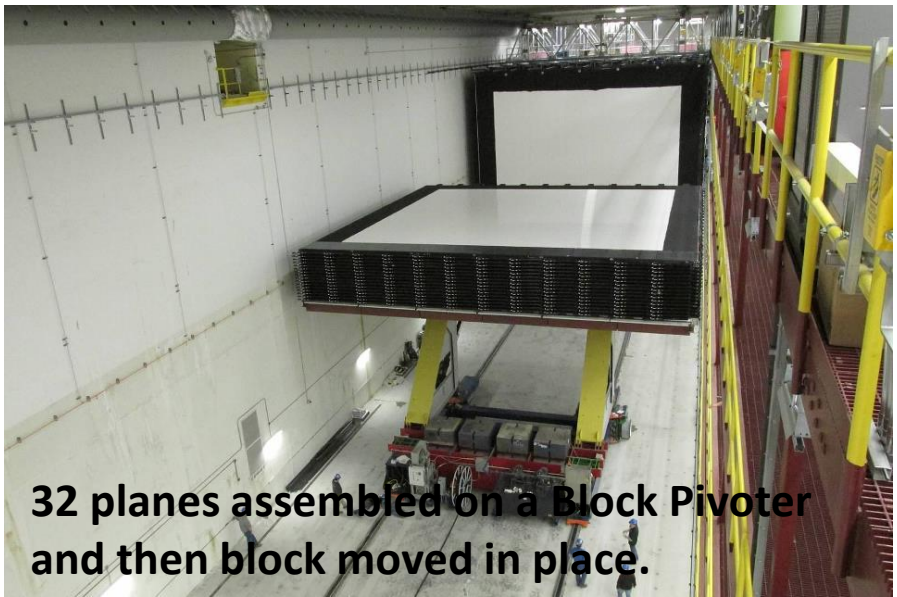
~5000 neutrino events from the NuMI beam were found.
First preliminary result of CC QE cross section measurement with NDOS was presented two months ago.

Far Detector Site

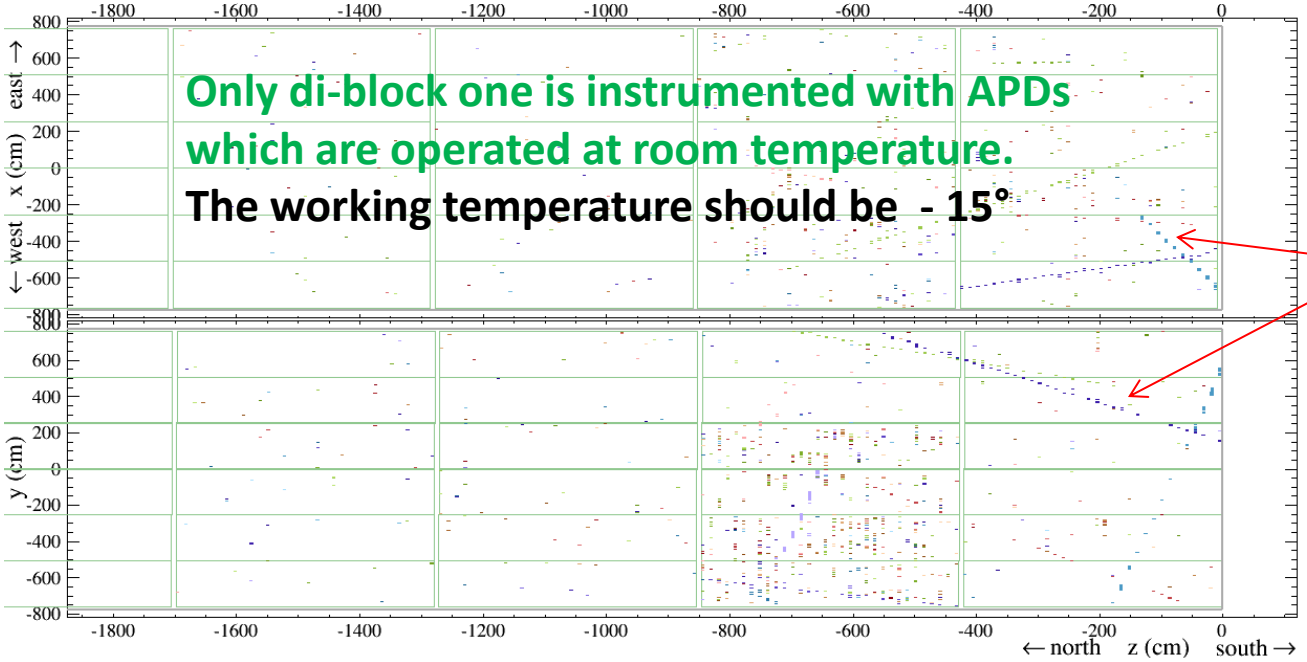
Far Detector Construction Status



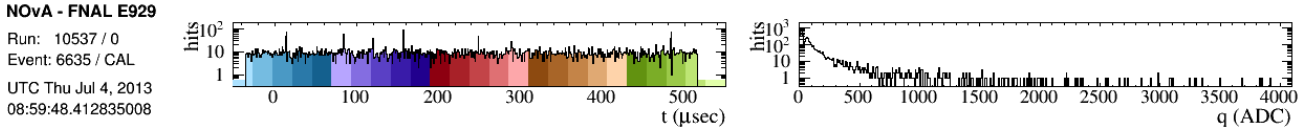
Production was started on July 26 2012



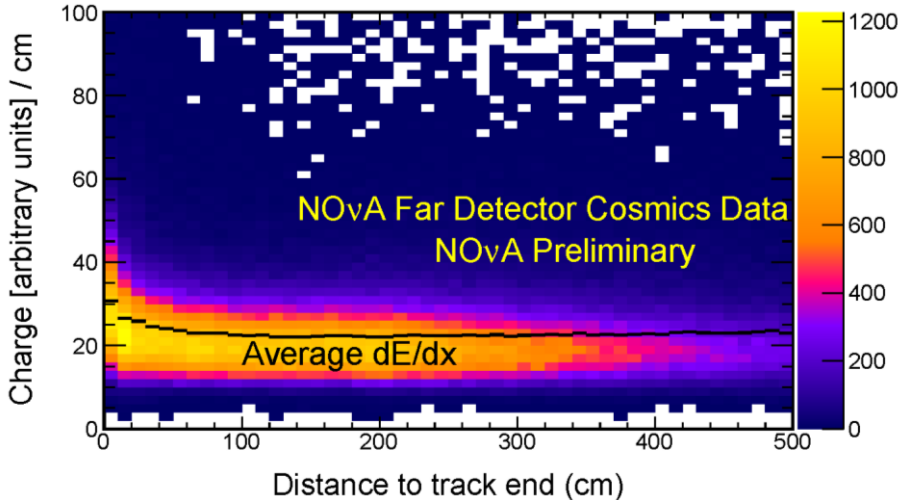
Far Detector Cosmics Events

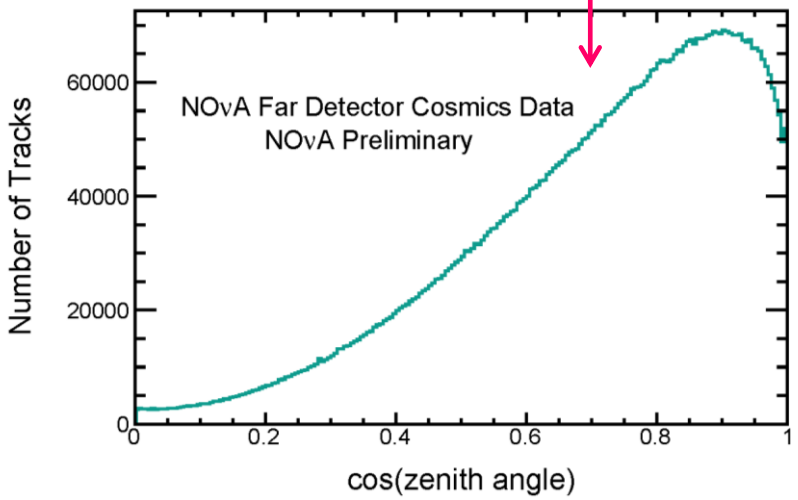


Cosmic muon tracks

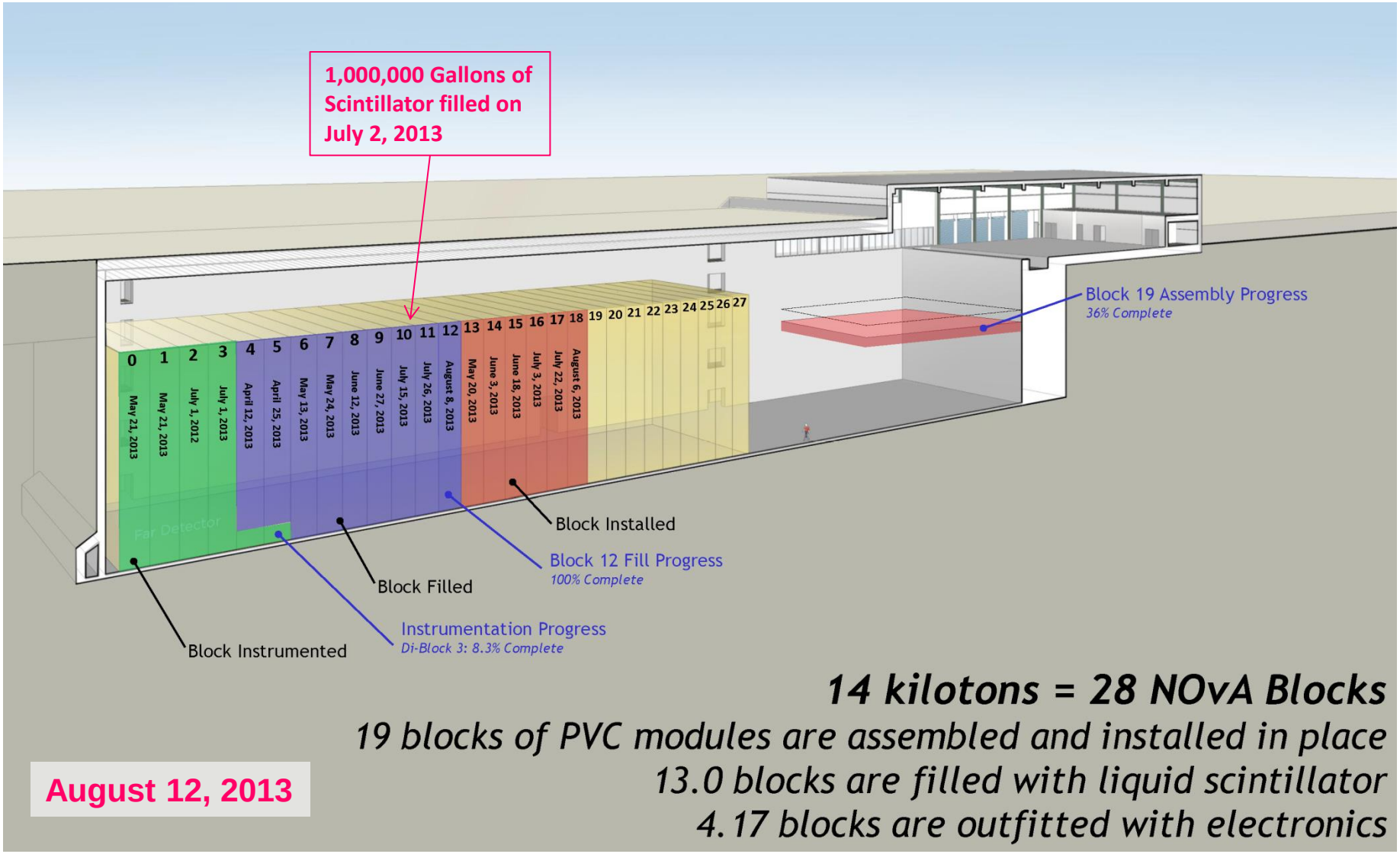


Zenith angle of muons with respect to the vertical direction



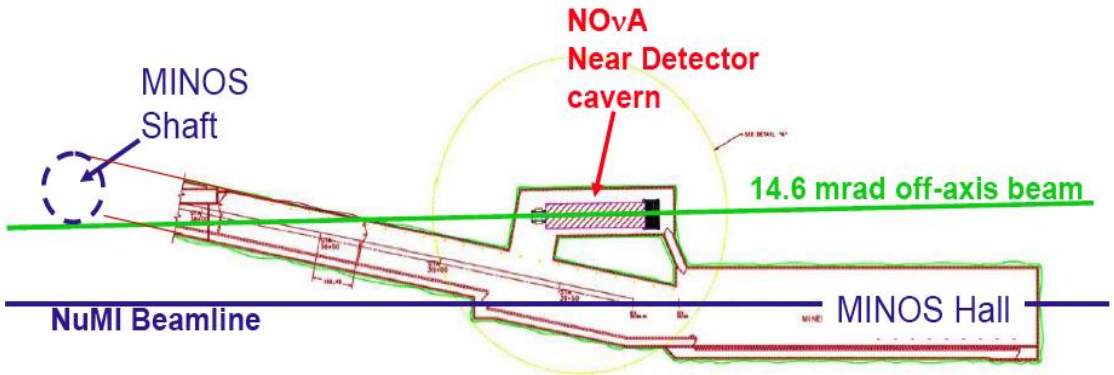


Far Detector Assembly Progress

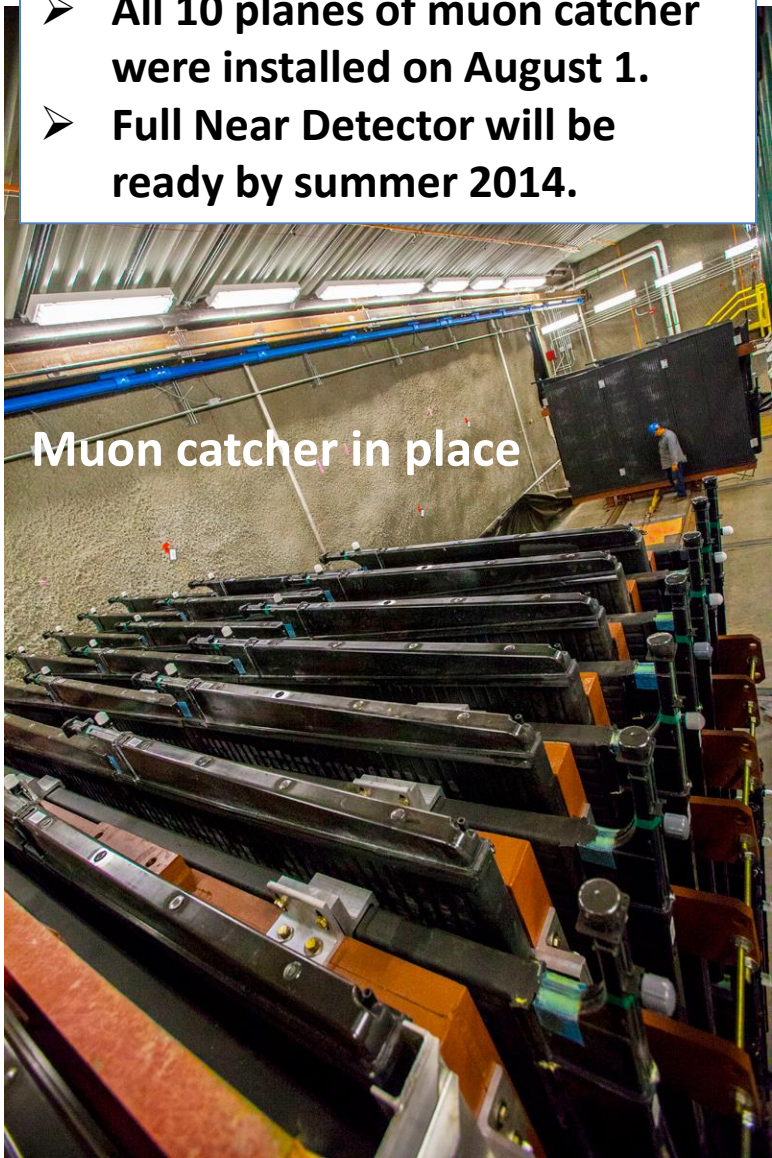


Near Detector Status

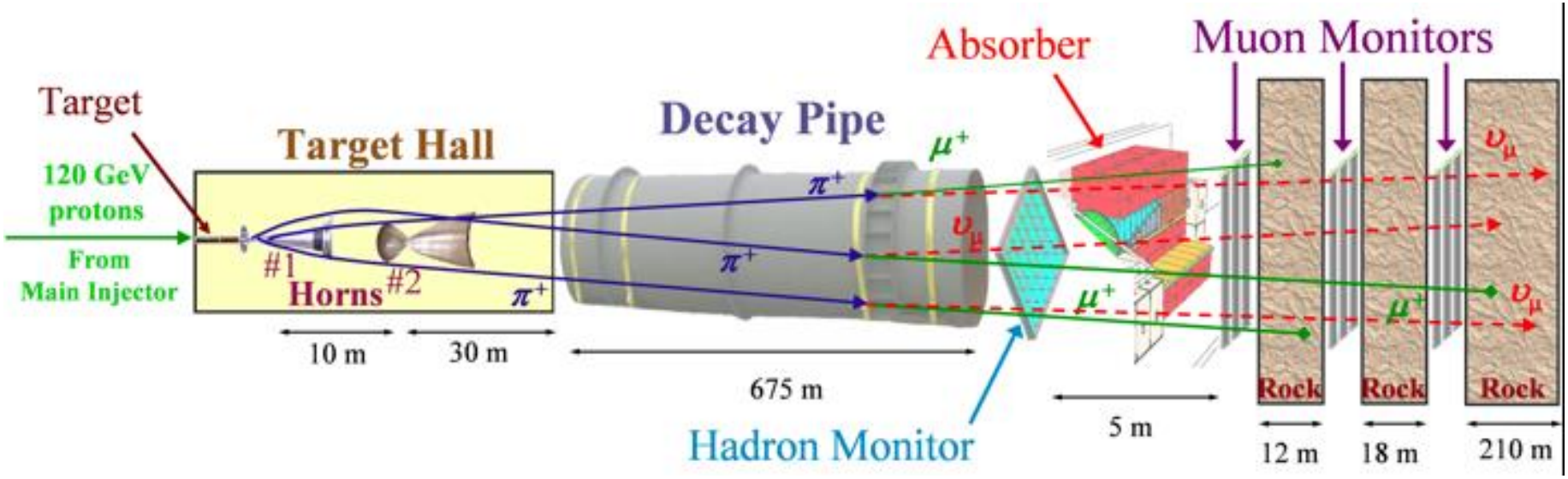
ND will be placed 105 m underground, in a new cavern to was excavated near the MINOS and Minerva ND's hall.



- **The cavern excavation and outfitting was finished in June.**
- **All 10 planes of muon catcher were installed on August 1.**
- **Full Near Detector will be ready by summer 2014.**



NuMI Beam upgrade



NuMI beam

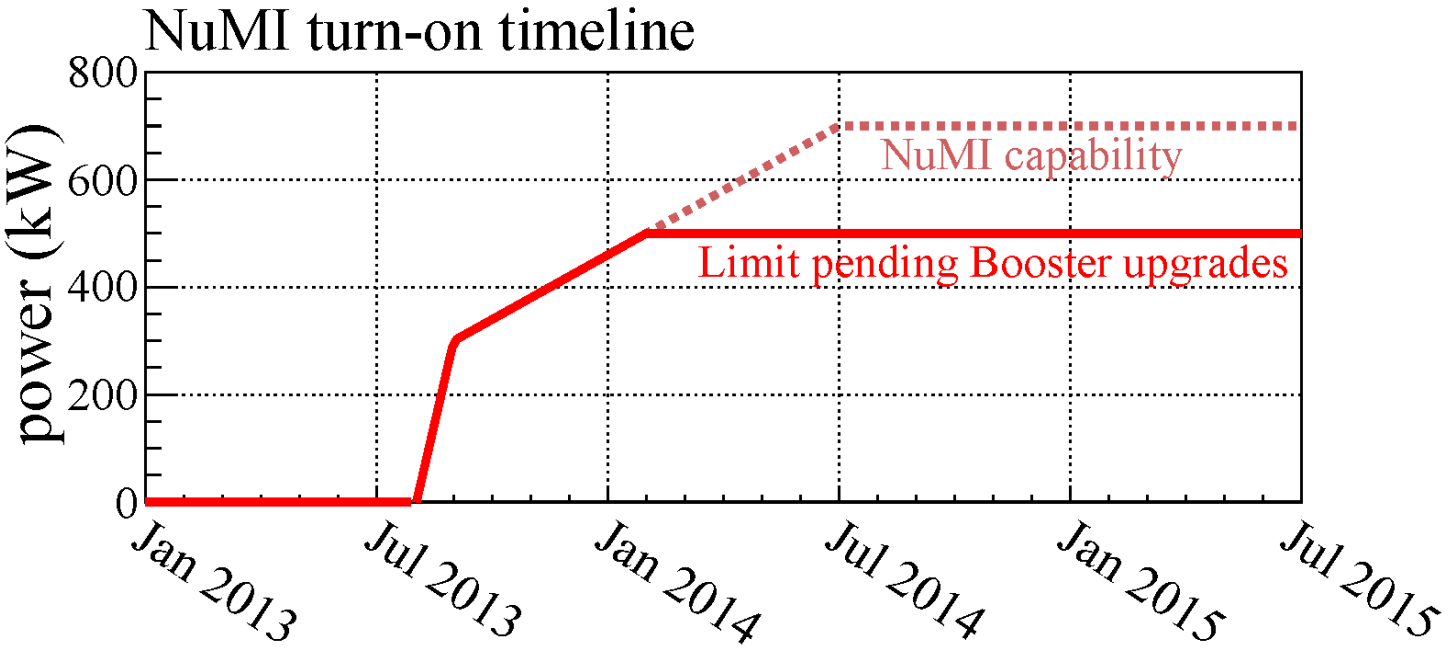
- Operating since 2005
- 10 µsec beam spill, every 2.2 sec
- Currently delivers 280 - 300 kW
- Recent experiments operating in beam: MINOS, MINERvA, ArgoNeut

Accelerator and NuMI beam upgrades:

- ✓ **700 kW power to NuMI beam**
- ✓ **Reduce cycle time from 2.2 to 1.33 seconds**
- ✓ **Increased intensity:**
  12 Booster batches up from 11
- ✓ **New high power target**
- ✓ **New horn, reconfigured for higher energy beam**
- ✓ **4.9×10^{13} proton/pulse or 6×10^{20} POT/year**

NuMI Beam Schedule

NOvA will start a first run on September 2013 with beam operating at 300 kW



Beam intensity will be increased up to 500 kW next year and to 700 kW in 2 years.

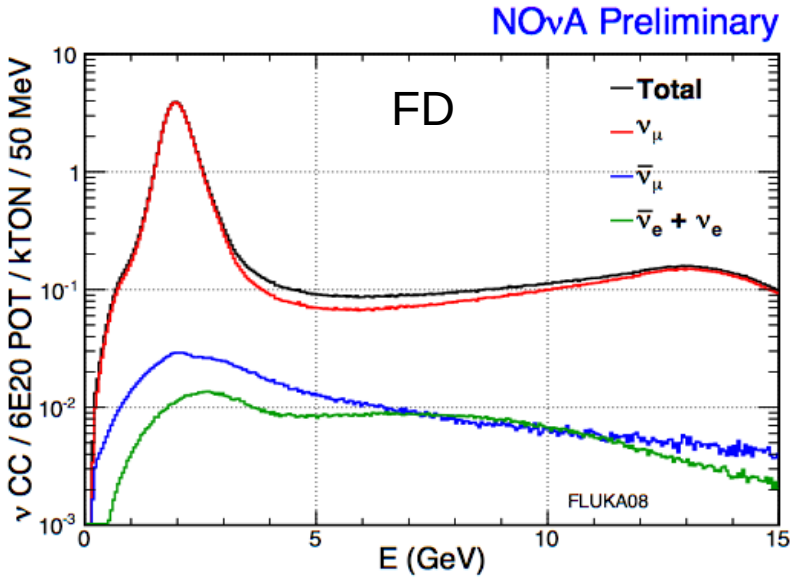
Far Detector mass will be added at a rate of about 1 kton/3 weeks.
Full installation of NOvA detectors will be completed in one year.

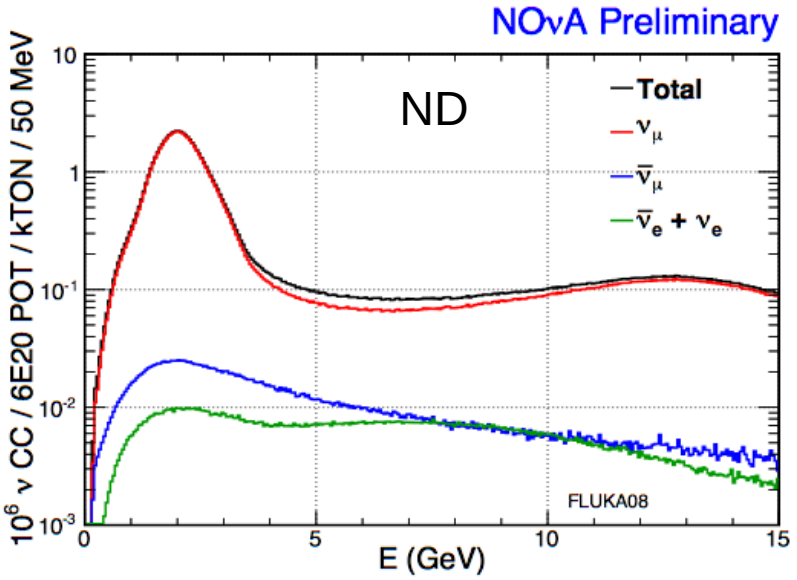
Summary

- NOvA has become the leading experiment at Fermilab.
- A large value of θ_{13} allows NOvA to make many measurements:
  - Determination of neutrino mass hierarchy.
  - Search for CP violation in neutrino sector.
  - Determination of the $\boldsymbol{\theta_{23}}$ octant.
  - More precise measurements of $\boldsymbol{\Delta m_{32}{}^2}$ and $\boldsymbol{sin^2(2\theta_{23})}$.
- NDOS prototype runs very successful.
- NOvA Far and Near Detectors are under construction:
  - 19 Far Detector blocks were installed.
  - Over 2 kton of FD instrumented and taking cosmic data.
  - The installation of FD will be finished by early next year and fully instrumented in summer 2014 .
  - Assembling of Near Detector was started. Full Near Detector will be ready by summer 2014.
- NOvA will start a data taking on September 2013.

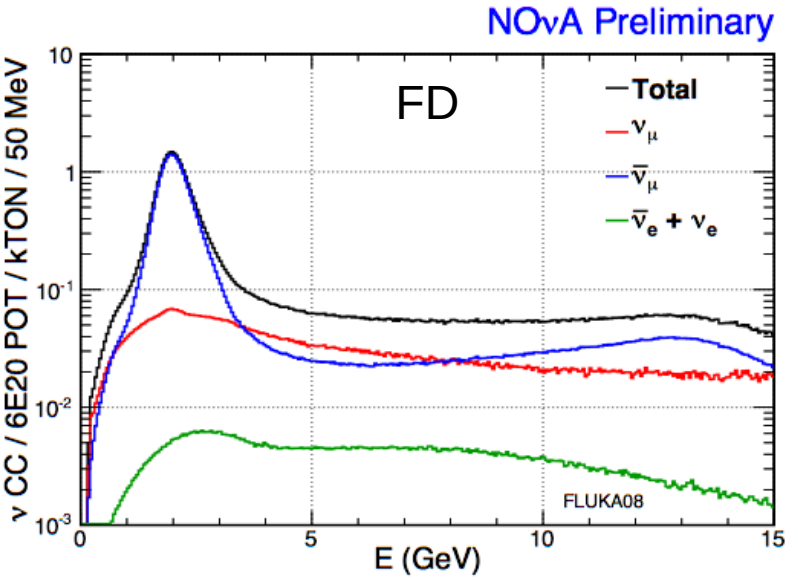
Backup slides

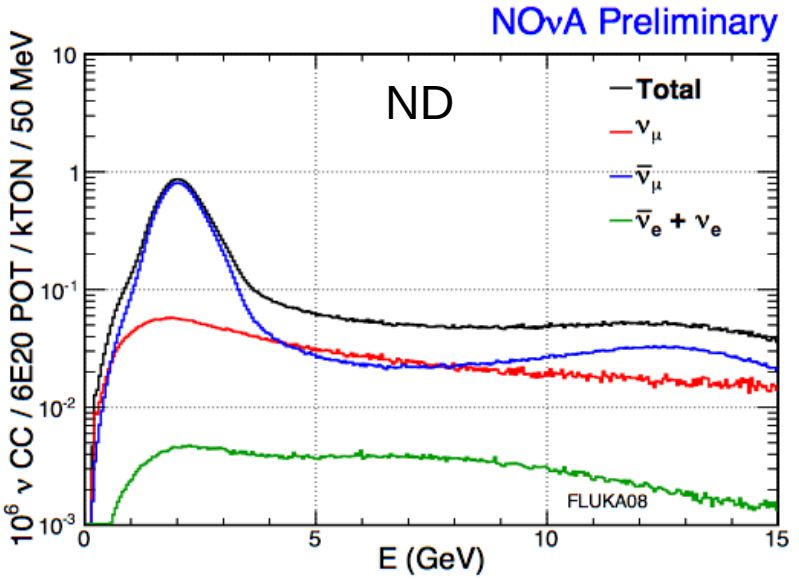
FHC ν CC





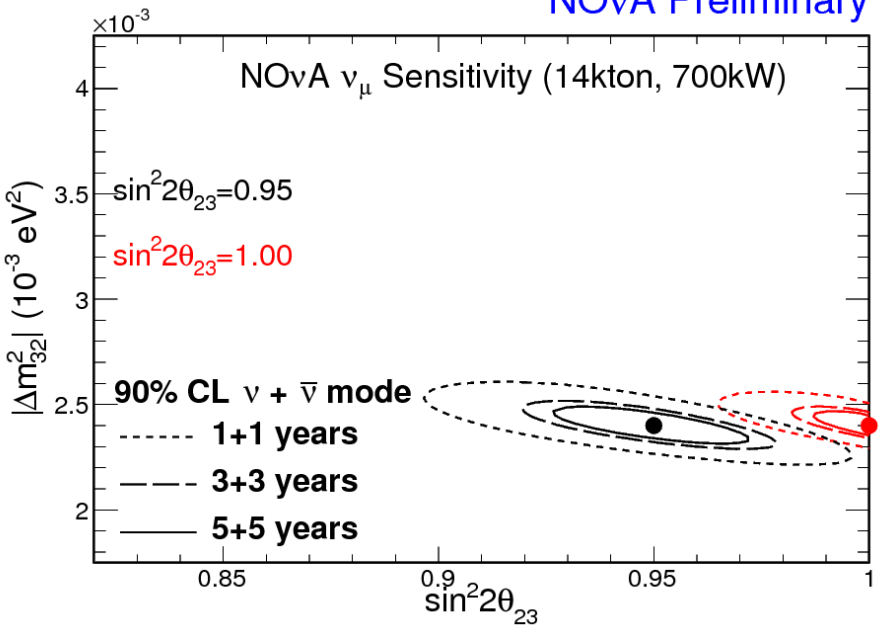
RHC ν CC



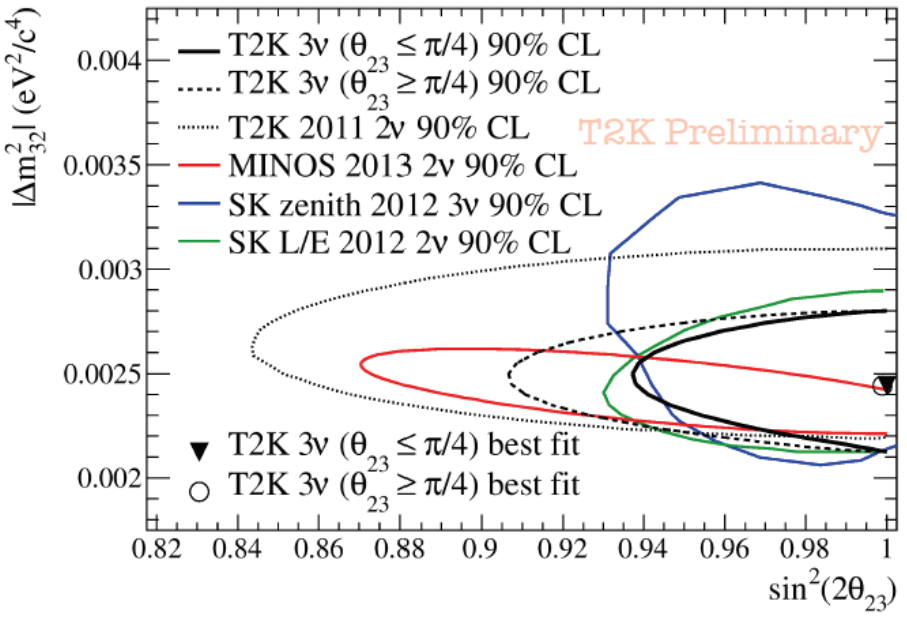


θ_{23} Sensitivity

NOνA Preliminary



Wilking, EPS July 2013



- **We expect to be able to surpass the current measurement of θ_{23} after 3+3 years of running.**
- **If $\sin^2(2\theta_{23}) = 1.00$, we expect to surpass the current best measurement after only 1+1 years of running.**
- **If $\sin^2(2\theta_{23}) = 0.95$, we will be able to exclude (at the 90% CL) maximal θ_{23} after 1+1 years of running.**