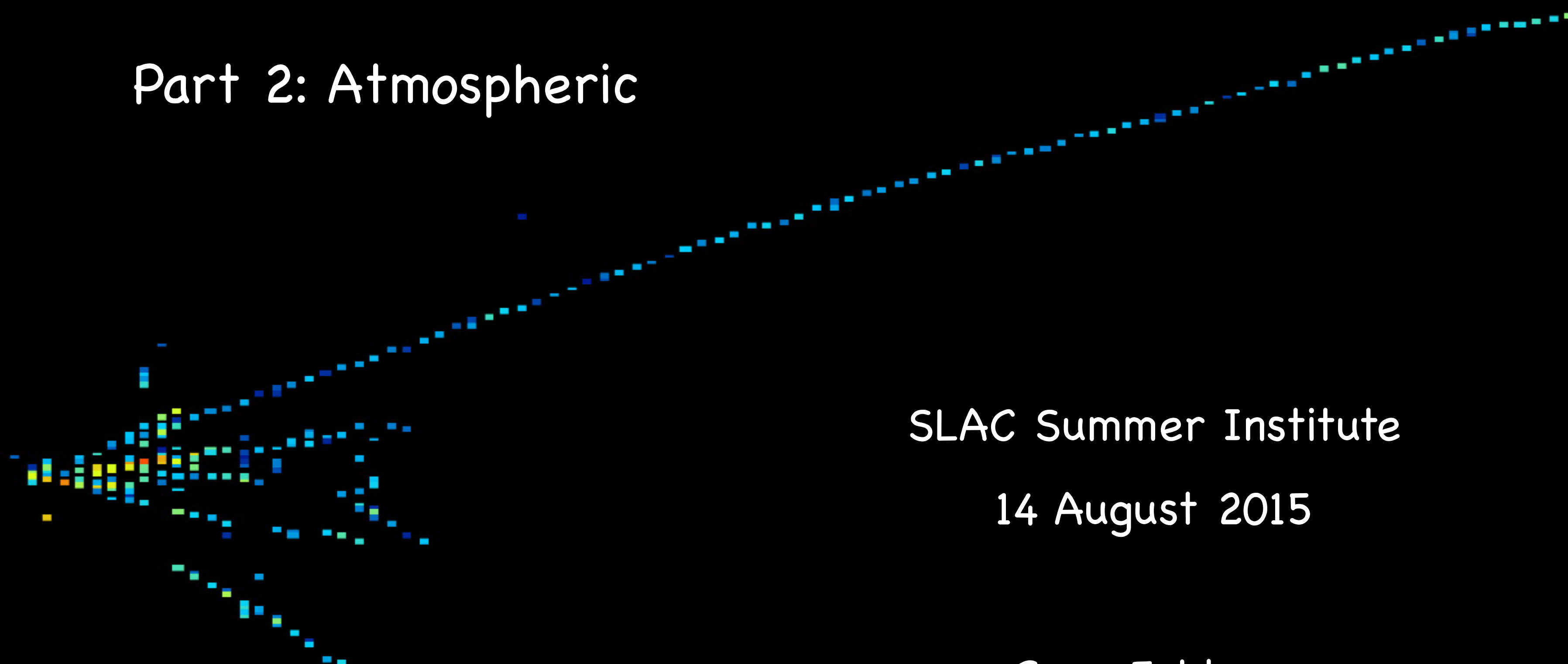
Long Baseline Neutrino Oscillations

Part 2: Atmospheric



ν_μ Charged Current Event
in the NOνA Detector

SLAC Summer Institute

14 August 2015

Gary Feldman

Accelerator Experiments

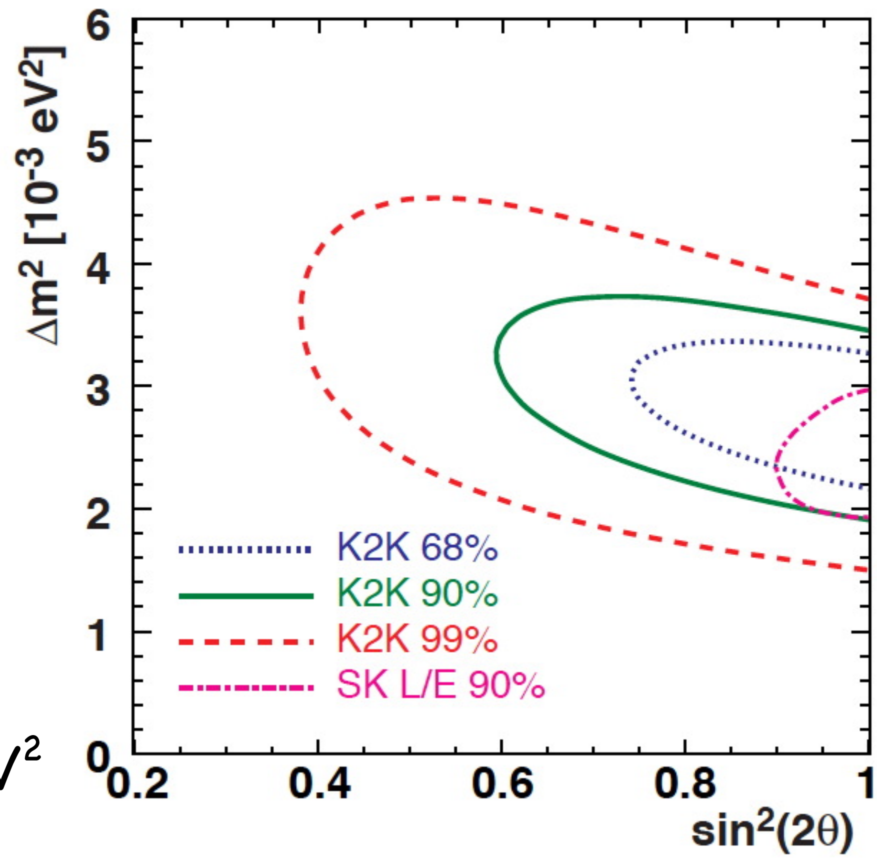
- We now turn to the study of the atmospheric mass region using accelerator beams. There are many advantages in using accelerator beams to study neutrino oscillations:
  - The distance is precisely known, taking half of the *L*/*E* uncertainty away.
  - The beam, mostly from pion decay, is typically 99% pure ν_μ. For example, atmospheric neutrino experiments cannot make a precise measurement of $\nu_\mu \to \nu_e$ oscillations because with roughly equal numbers of ν_μ's and ν_e's, the ν_μ's typically oscillate to ν_e's as often as the ν_e's oscillate to ν_μ's .
  - Focused beams allow the independent study of neutrinos and antineutrinos.
  - Narrow band beams are possible, reducing backgrounds.

K2K Experiment

- K2K (KEK to Kamioka) was the first long baseline accelerator experiment.
- Like almost all long baseline accelerator experiments, it used a small near detector to measure the neutrinos before they had time to oscillate and a large far detector to measure them after they had oscillated. Using a Monte Carlo corrected far/near ratio eliminates many systematic uncertainties.
- For K2K, the far detector was Super-Kamiokande and the near detector was a small water Cerenkov detector. The baseline was 250 km. The experiment ran between 1999 and 2004.

K2K Experiment Results

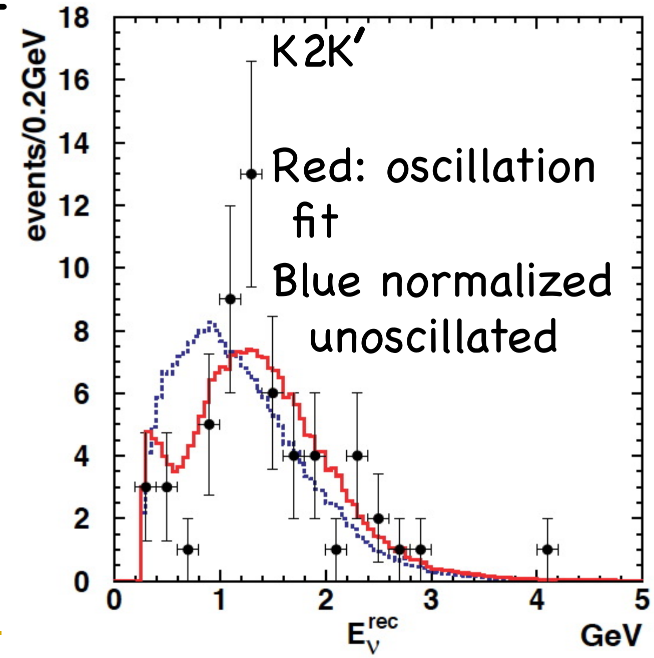
- The K2K beam was supplied by a 12 GeV proton synchrotron at KEK. The total recorded data for the experiment was 0.9×10^{20} protons on target (PoT).
- The central values were
  $\Delta m^2_{atm} = 2.8 \times 10^{-3}\ \text{eV}^2$
  $\sin^2(2\theta_{23}) = 1.0$
- SK central values were
  $\Delta m^2_{atm} = (2.0 \text{ to } 2.5) \times 10^{-3}\ \text{eV}^2$
  $\sin^2(2\theta_{23}) = 1.0$



M. H. Ahn et al., Phys. Rev. D 74, 072003 (2006)

Note on Maximal Disappearance

- In a 2-flavor analysis, the disappearance is proportional to $\sin^2(2\theta)$, which is obviously bounded by one. However, even for maximal disappearance, $\sin^2(2\theta) = 1$, the data will not normally go to zero at the oscillation maximum due to backgrounds and energy smearing. Thus it is possible for the oscillation fit to get $\sin^2(2\theta) > 1$, in which case the experiment will report $\sin^2(2\theta) = 1$.
- K2K actually got $\sin^2(2\theta) = 1.19$.
- To what extent the mixing is maximal is an important issue, particularly for $\nu_\mu \rightarrow \nu_e$ oscillations.

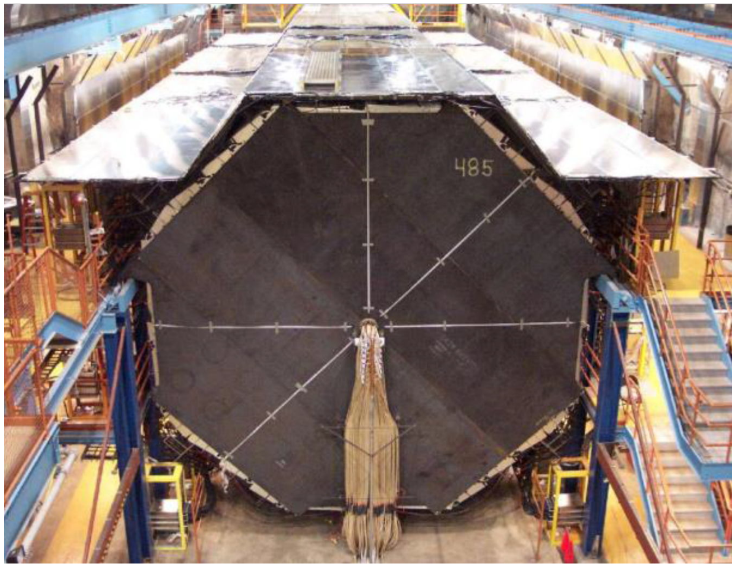


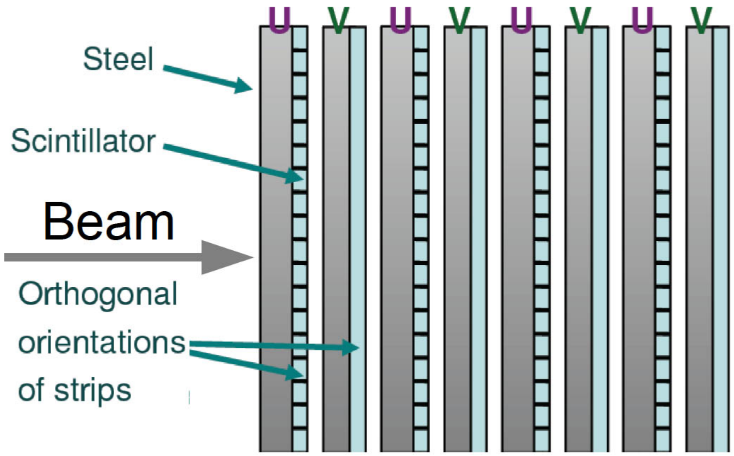
The MINOS Experiment

- The other 1st generation long baseline accelerator experiment of note is MINOS (Main Injector Neutrino Oscillation Search) at Fermilab, with the far detector in the Soudan mine in northern Minnesota, 735 km from Fermilab.
- This experiment was proposed in 1994 under the assumption that Δm^2_{atm} was much larger than it turned out to be, but with sufficient flexibility for all possibilities.
- MINOS ran from 2005 to 2012 and restarted as MINOS+ in 2013.

MINOS Far Detector

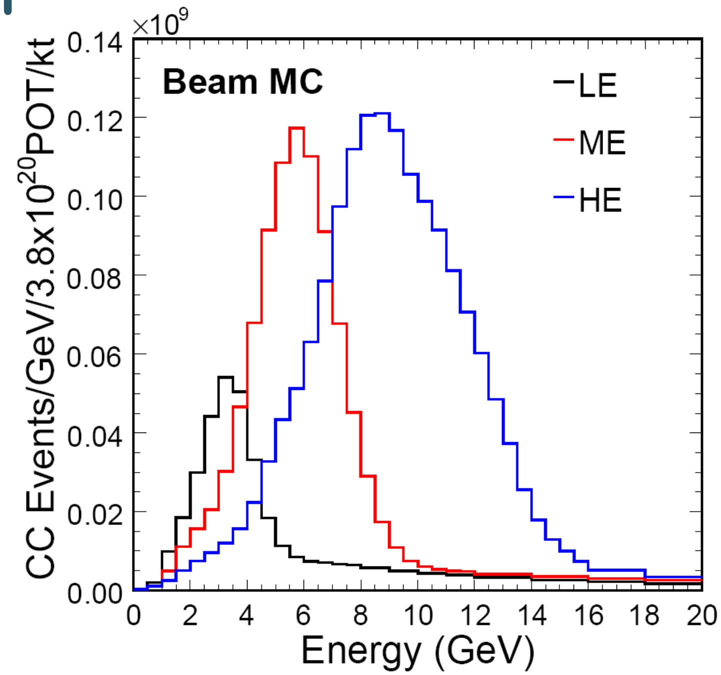
- The MINOS far detector is a magnetized steel-scintillator sandwich detector:
  - 8 m octagonal design
  - 484 layers of 2.54 cm iron plates
  - 4.1 cm-wide scintillator strips with WLS fiber readout at both ends.
  - 8 fibers summed on each pixel of a 16-pixel photomultiplier.
  - Toroidal magnetic field, $\langle B \rangle = 1.3$ T
  - Total mass of 5.4 kt
- The near detector is smaller, but functionally the same.

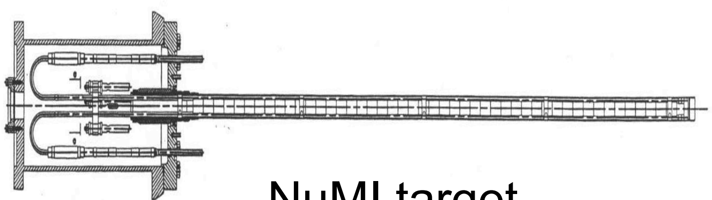




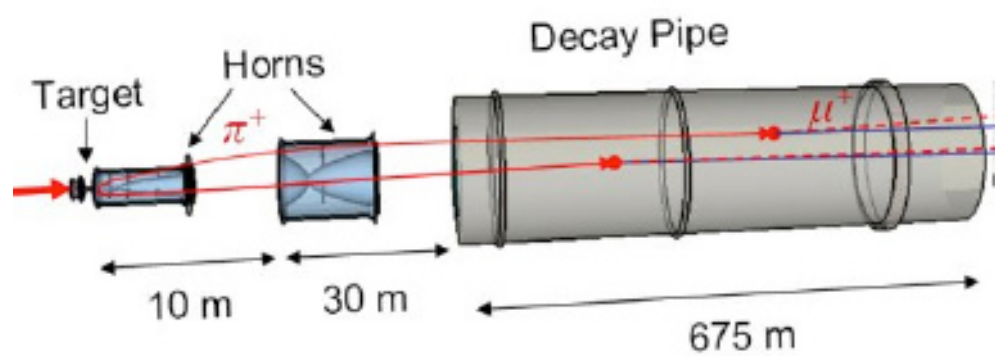
120 GeV NuMI Beam

- The NuMI (Neutrinos from the Main Injector) beam was built to be flexible by having a target that could move back and forth to give different neutrino spectra.
- MINOS ran with the low energy beam.





NuMI target

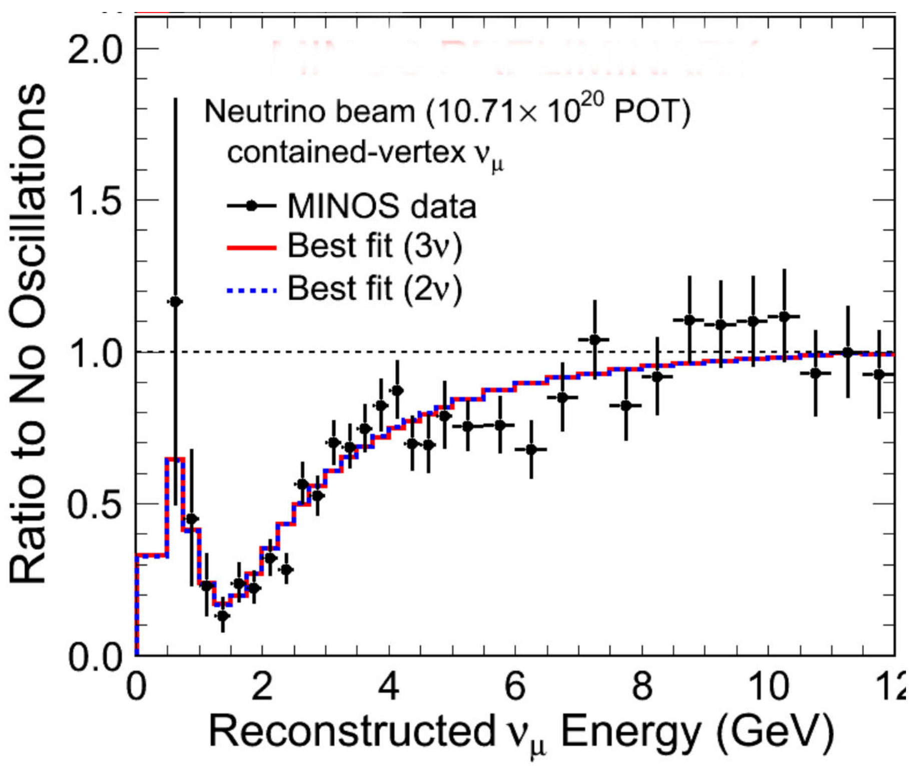


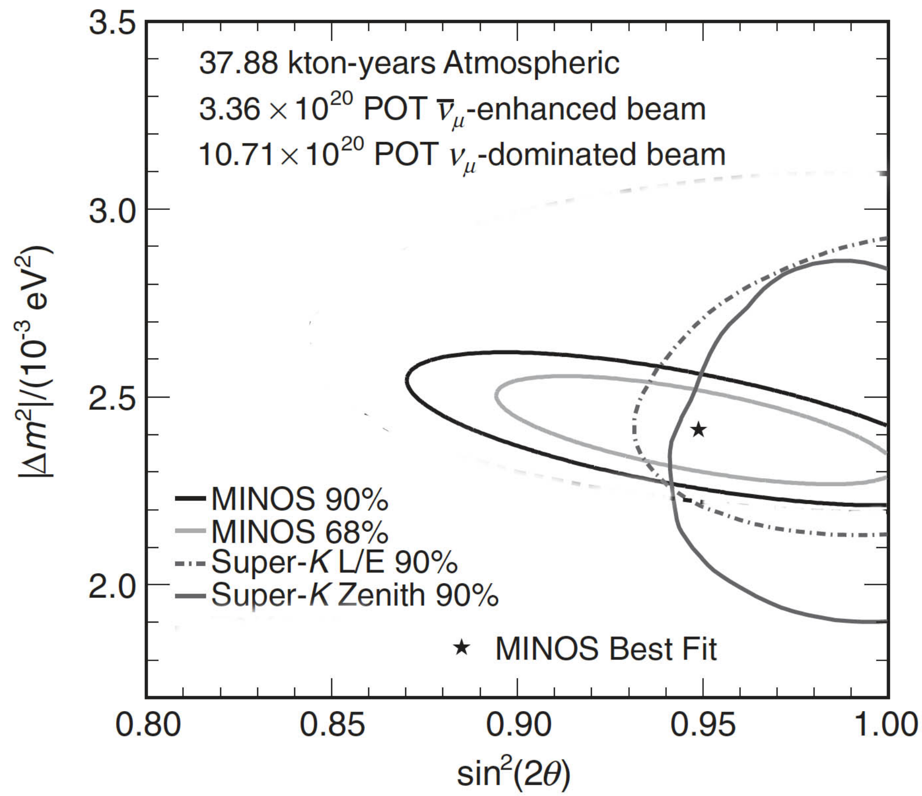
MINOS Final ν_μ Disappearance Data

$$\Delta m^2_{atm} = (2.41 \pm 0.10) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2(2\theta_{23}) = 0.950 \pm 0.036$$

Survival Probability





P. Adamson et al., Phys. Rev. Lett. 110, 2518011 (2013)

$\nu_\mu \rightarrow \nu_e$ Oscillations

- The MINOS experiment was the first that made significant progress on measuring $\nu_\mu \rightarrow \nu_e$ oscillations.
- Up to now, we have been able to use two flavor oscillations. However, $\nu_\mu \rightarrow \nu_e$ oscillations require 3 flavor oscillations. I want to briefly review this somewhat complicated formalism and it consequences.
- There are 4 crucial parameters that control these oscillations: $\sin^2(2\theta_{13})$, sign(Δm^2_{23}), δ_{CP}, $\sin^2\theta_{23}$. The first of these is well measured by reactor experiments, with the average $\sin^2(2\theta_{13}) = 0.086 \pm 0.005$.
- At present, the other 3 parameters are the province of accelerator experiments.

$P(\nu_\mu \rightarrow \nu_e)$ in Vacuum

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2_{31}L/E)$$ Atmospheric

$$P_2 = \cos^2(\theta_{23})\sin^2(2\theta_{12})\sin^2(1.27\Delta m^2_{21}L/E)$$ Solar

$$P_3 = \mp J\sin(\delta)\sin(1.27\Delta m^2_{31}L/E)$$

$$P_4 = J\cos(\delta)\cos(1.27\Delta m^2_{31}L/E)$$

Atmospheric-Solar Interference (for P_3 and P_4)

$$\text{where } J = \cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23}) \times \sin(1.27\Delta m^2_{21}L/E)\sin(1.27\Delta m^2_{31}L/E)$$

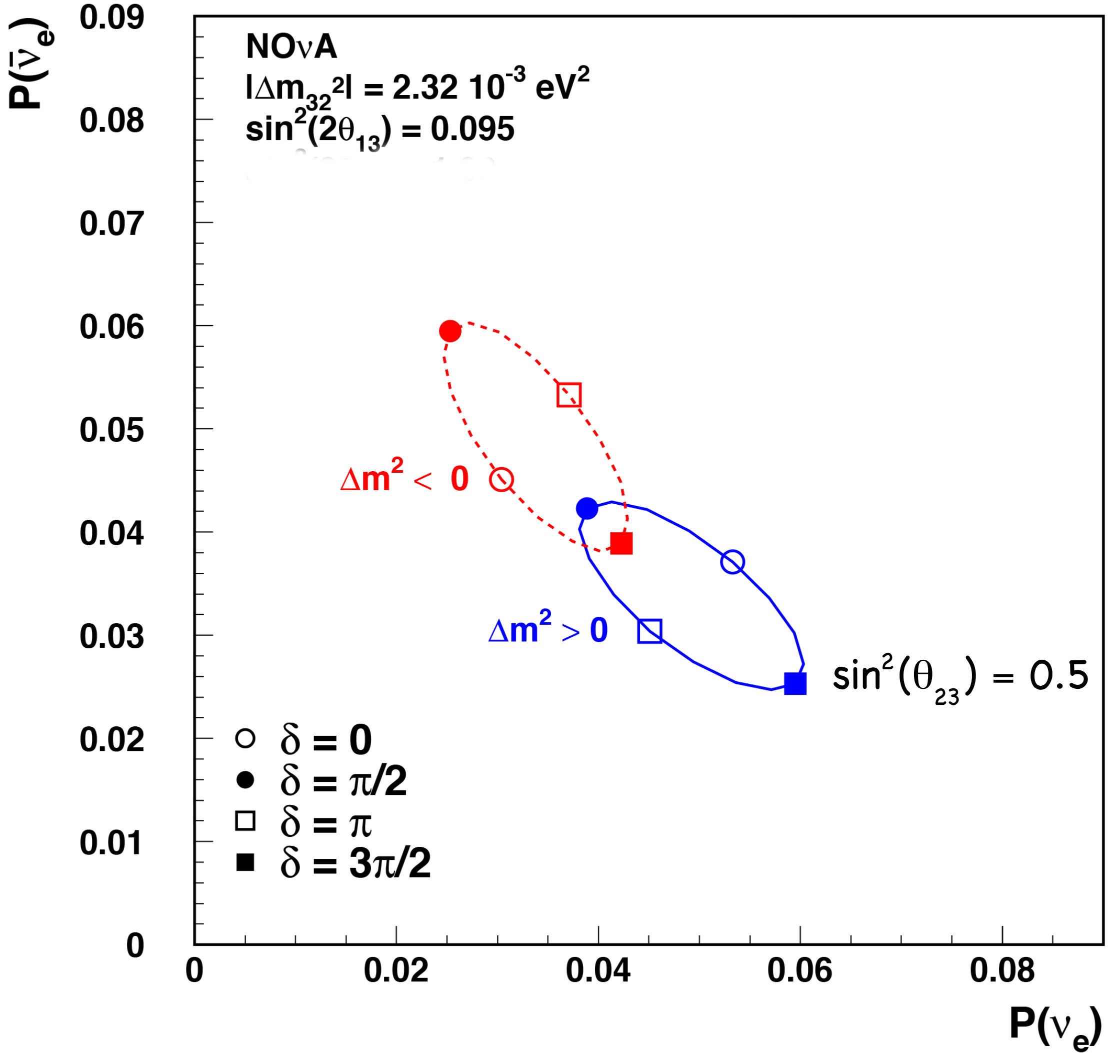
$P(\nu_\mu \to \nu_e)$ in matter

- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass ordering and antineutrinos with inverted mass ordering.

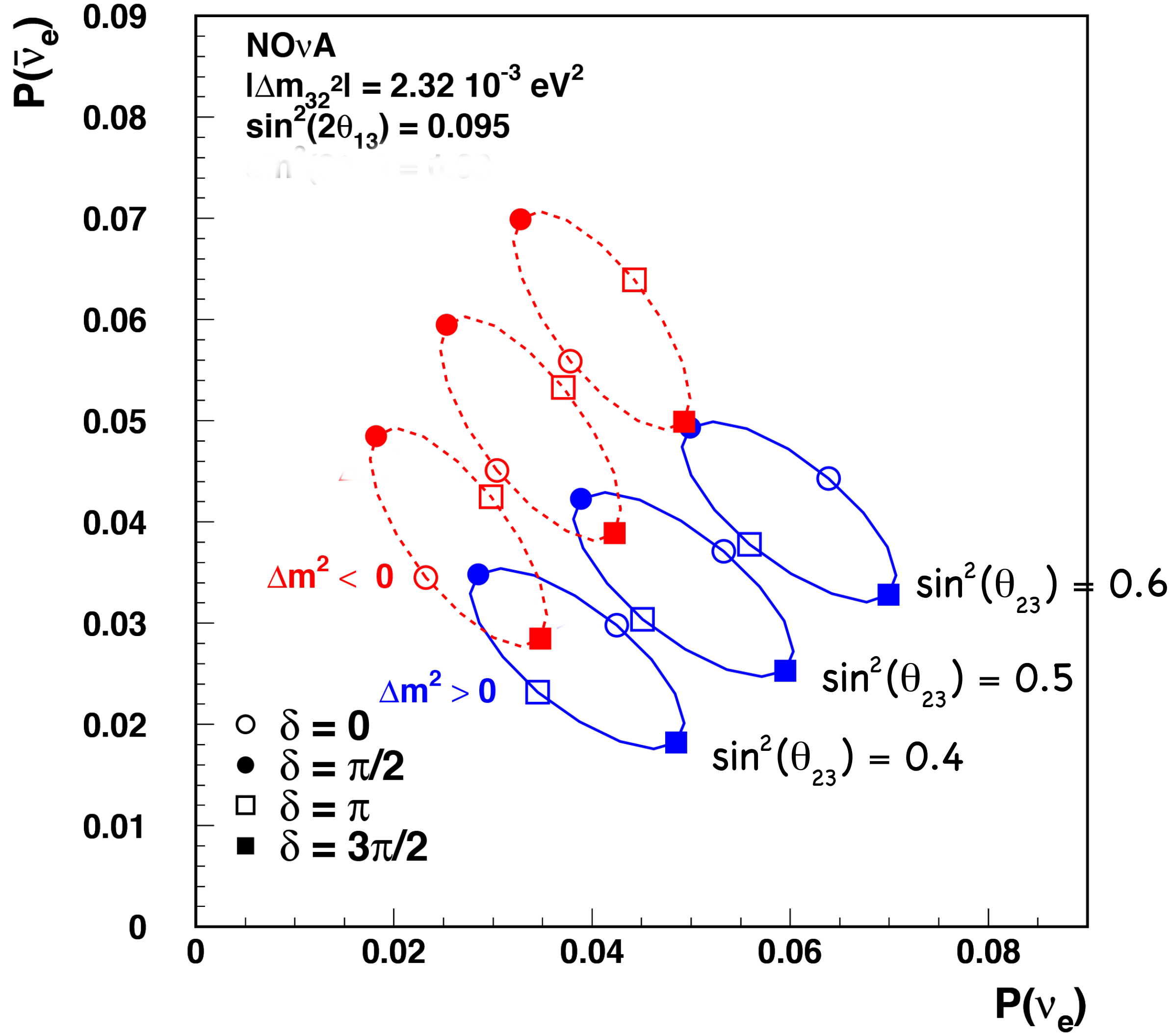
$$E_R = \frac{\Delta m_{31}}{2\sqrt{2}G_F\rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

At oscillation maximum, this is about a ±27% effect for MINOS, a ±11% effect for T2K, and a ± 30% effect for NOvA. The effect decreases for neutrino energies above the oscillation maximum.

Bi-probability Plot



Bi-probability Plot

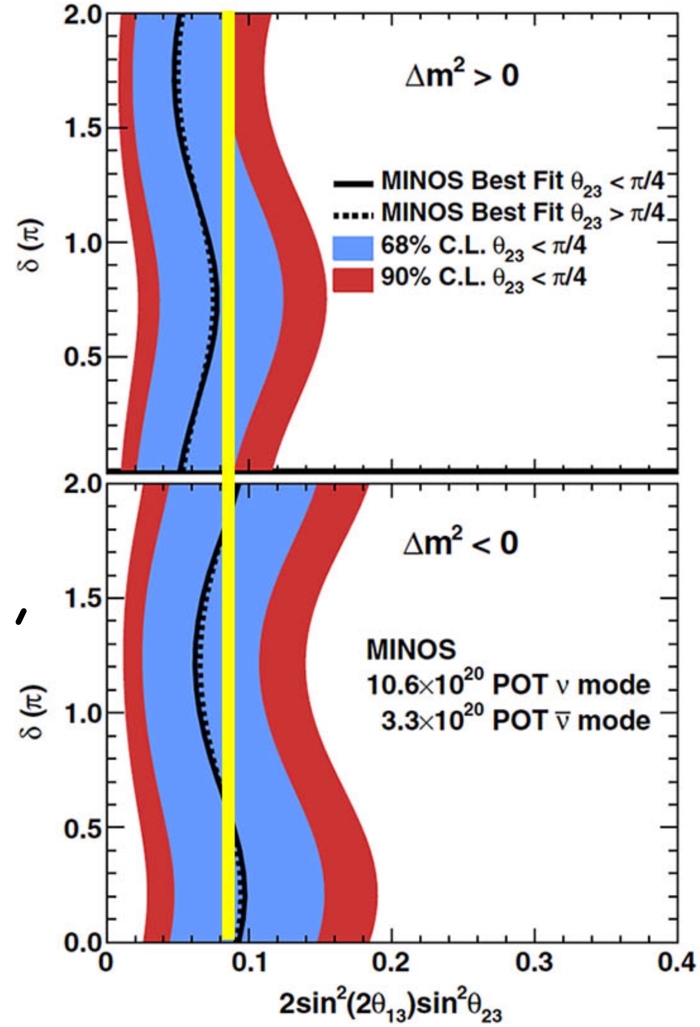


Final MINOS $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- MINOS was not designed to identify electron CC events. It is difficult to do this with 1.5 radiation length steel plates.
- Nonetheless, through heroic efforts, it obtained useful information.
- In neutrino running it found 152 events, including an estimated background of 128 events. In antineutrino running, it found 20 events, including an estimated background of 17.5 events.
- These numbers correspond to 1:5.2 and 1:9.5 signal to background ratios

Final MINOS $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- The plot to the right shows the results for both mass orderings and as a function of δ_{CP}.
- The yellow line (mine) indicates the present 1σ constraint from the reactor experiments, if $\sin^2(2\theta_{23}) = 1$. If $\sin^2(2\theta_{23}) = 0.95$, then the yellow line moves one small horizontal tic to the left or right. In either case, the MINOS data are consistent with both mass orderings and all δ_{CP} within the 90% C.L.



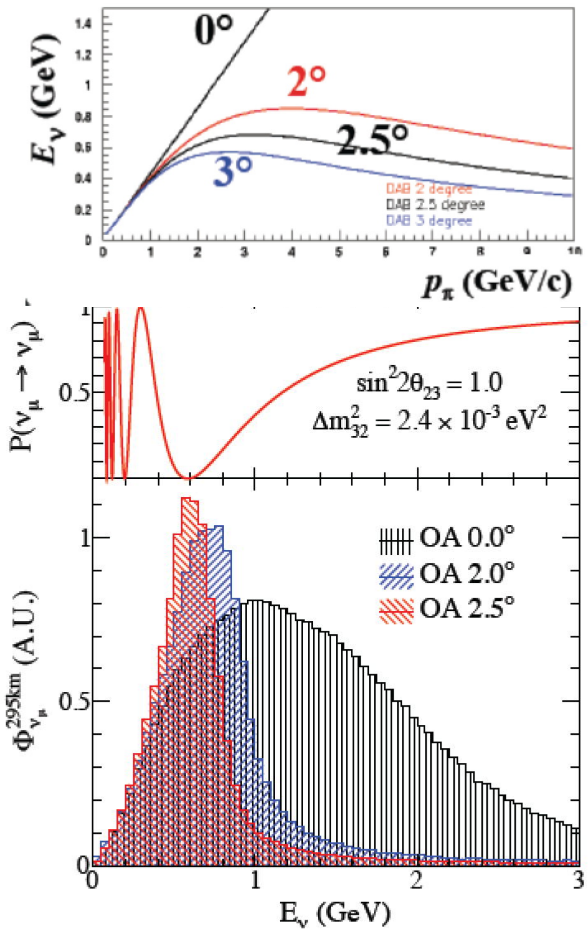
P. Adamson et al., *Phys. Rev. Lett.* **110**, 171801 (2013)

T2K and NOνA Experiments

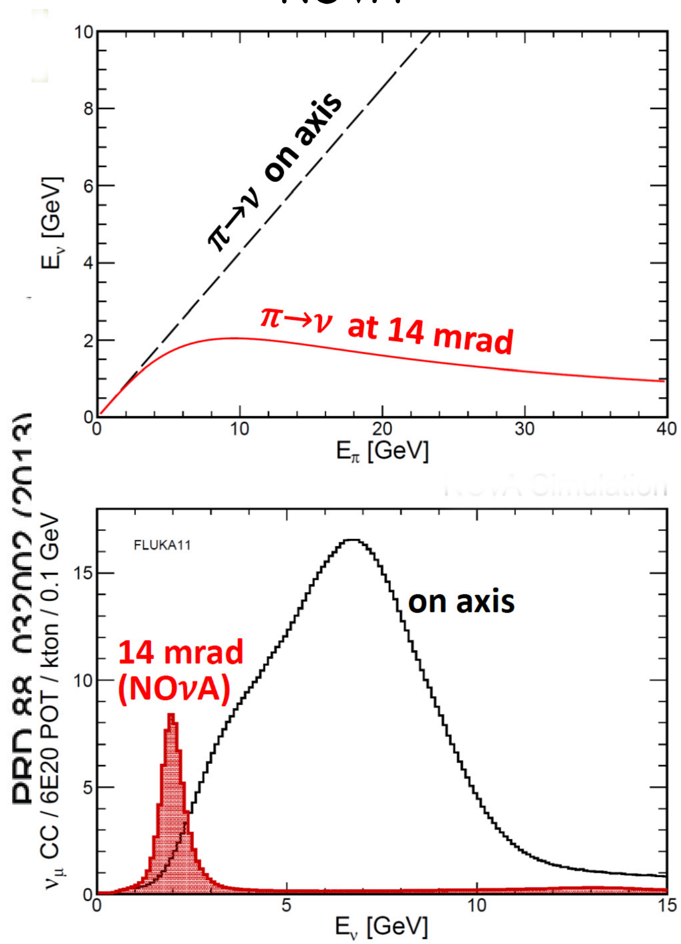
- We now turn our attention to the two 2nd generation accelerator oscillation experiments, T2K and NOνA.
- Both experiments are optimized to measure $\nu_\mu \rightarrow \nu_e$ oscillations, which we have seen are the key to measuring the 3 remaining poorly known "standard model" parameters. Both will also make precise measurements of ν_μ disappearance.
- Both also use a technique, as far as I know, was first proposed by Brookhaven in a shoot-out with MINOS (which they lost). That technique is to site the detectors off of the center of beam, which produces a narrow band beam about the oscillation maximum, yielding higher neutrino flux and lower backgrounds.

Off-Axis Beams

T2K



NOνA



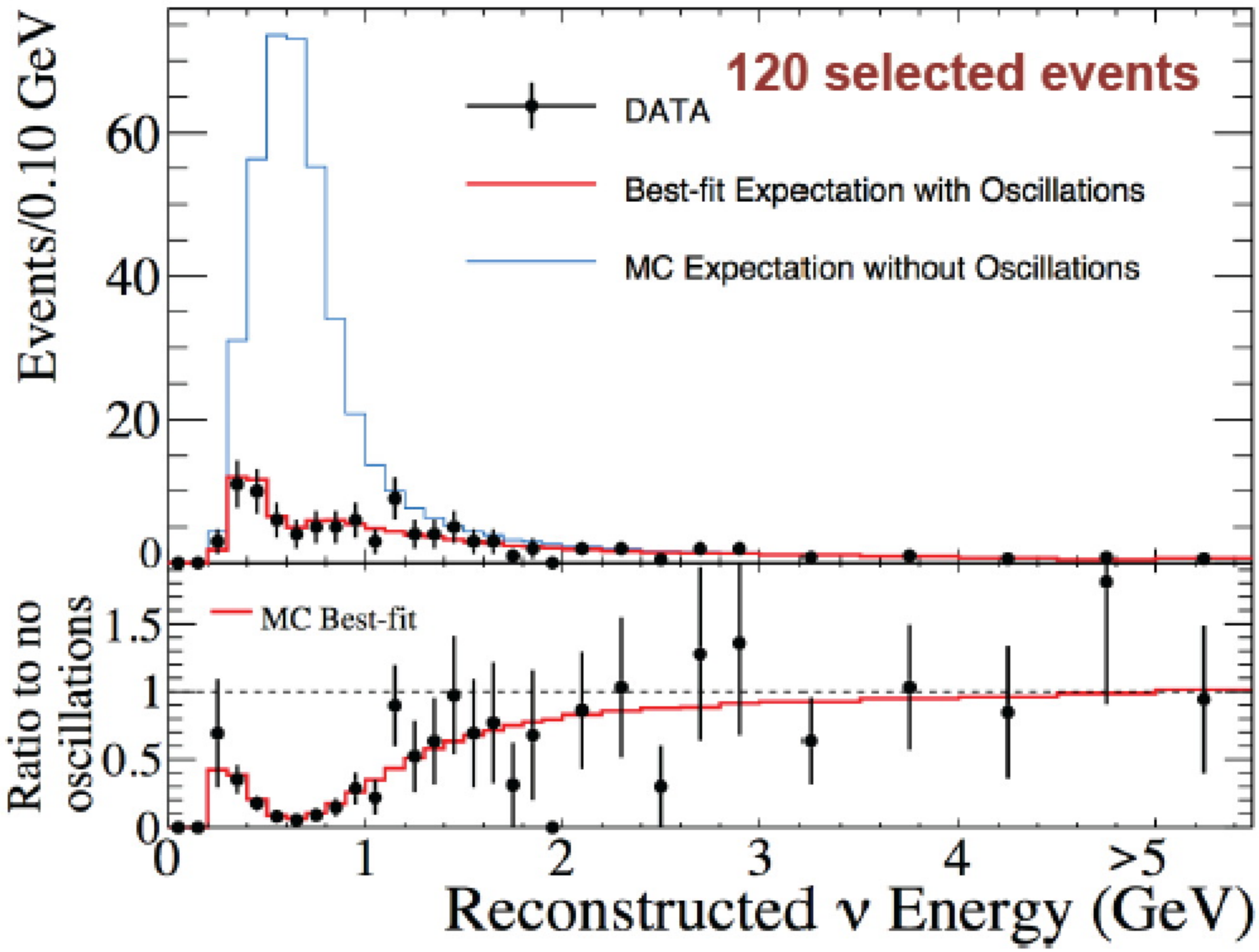
Note: T2K and NOνA talks in the topical conference next Wednesday Afternoon.

Thus, I will be short on technical details.

The T2K Experiment

- T2K (Tokai to Kamioka) is the follow-on experiment to KEK. The neutrino beam is created by a 30 GeV proton beam from the J-PARC (Japan Proton Accelerator Complex) 50 GeV synchrotron. Like KEK, the far detector is Super-Kamiokande, 295 km from J-PARC. The near detector is magnetized and contains fine-grained tracking and calorimetry.
- T2K began running in 2010, but had two serious interruptions: First the earthquake and tsunami in 2011 and then a radiation incident in another beam line in 2013.

T2K ν_μ Disappearance Results



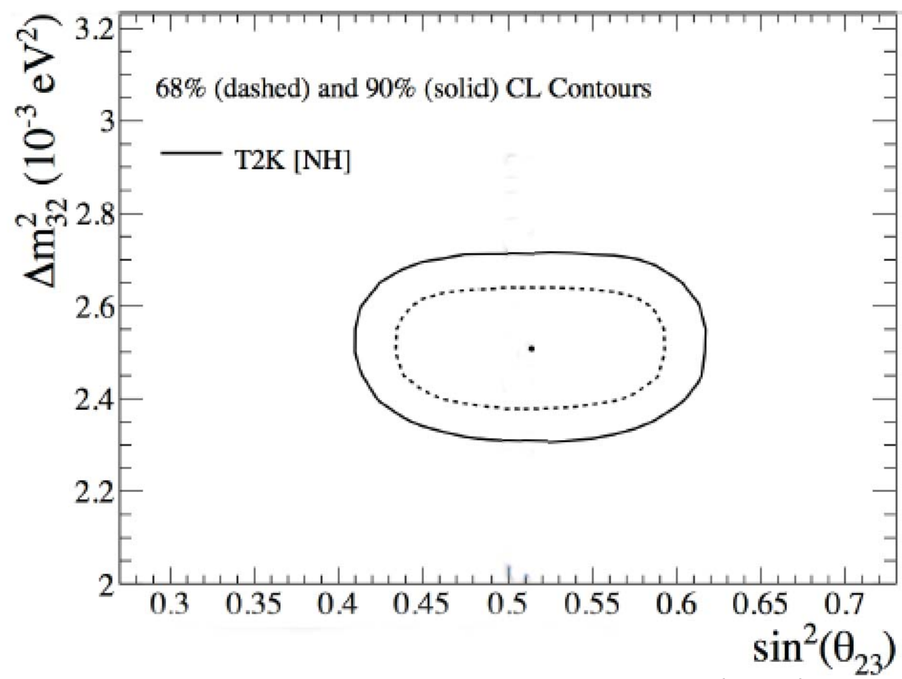
K. Abe et al., Phys. Rev. Lett. 112, 181801 (2014)

T2K ν_μ Disappearance Results

$$\Delta m^2_{32} = \begin{cases} (2.51 \pm 0.10) \times 10^{-3}\ \text{eV}^2\ \text{NO} \\ (2.48 \pm 0.10) \times 10^{-3}\ \text{eV}^2\ \text{IO} \end{cases}$$

$$\sin^2(\theta_{23}) = \begin{cases} 0.514 \pm 0.056\ \text{NO} \\ 0.511 \pm 0.055\ \text{IO} \end{cases}$$

- Displaying results in $\sin^2(\theta_{23})$ instead of $\sin^2(2\theta_{23})$ as part of a 3-flavor analysis is the current standard. My problem with it is that it contains no information other than the 2-flavor measurement combined with the reactor measurement of $\sin^2(2\theta_{13})$. It also hides a physical boundary.



K. Abe et al., *Phys. Rev. Lett.* **112**, 181801 (2014)

T2K ν_μ Disappearance Results

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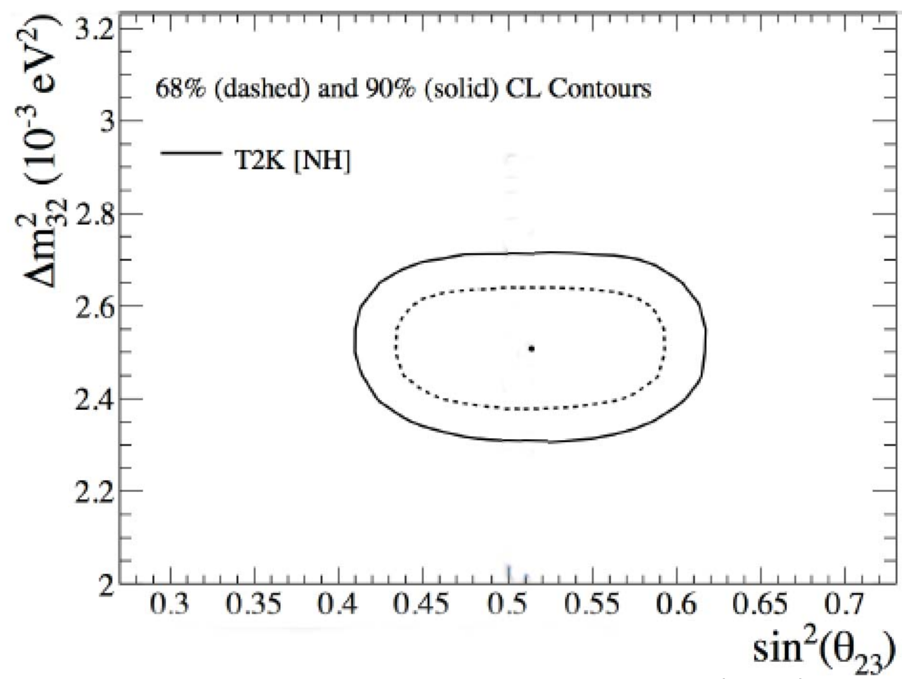
$$\sin^2(\theta_{23}) = \begin{cases} 0.514 \pm 0.056\ \text{NO} \\ 0.511 \pm 0.055\ \text{IO} \end{cases}$$

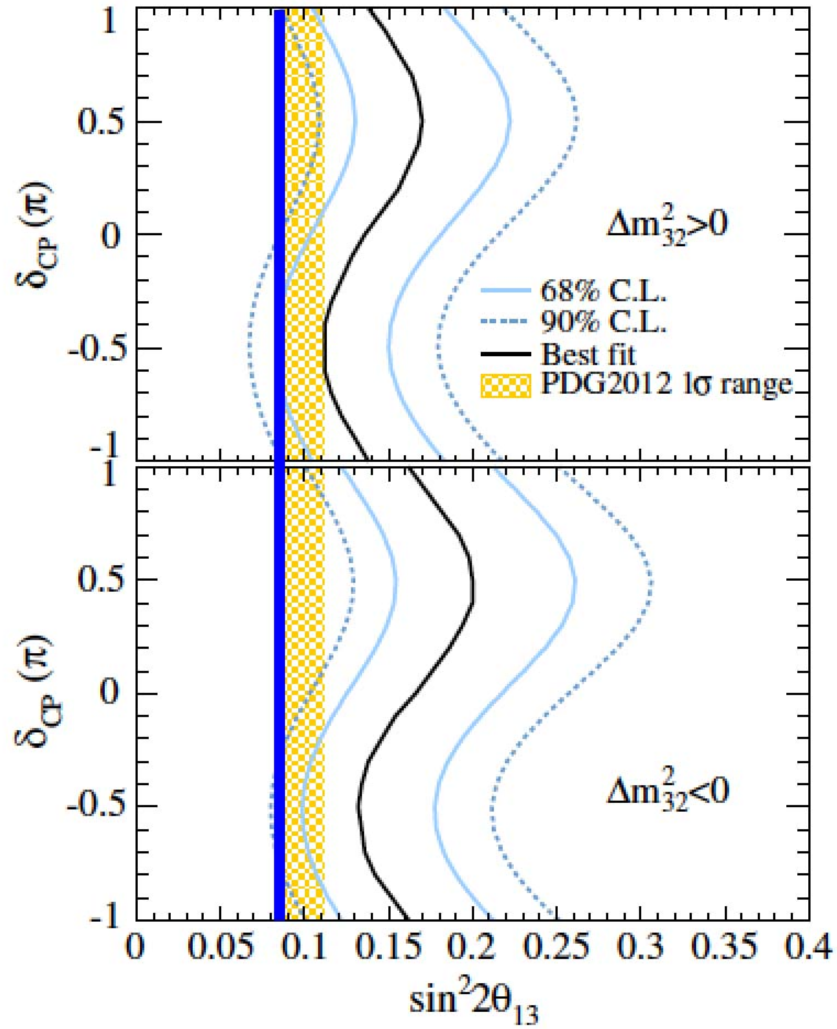
- I do not understand the small difference in the mass measurements. There are two small effects that I think go in opposite directions.
- The numbers for $\sin^2(\theta_{23})$ are just a way of saying that the fit was in the unphysical region. It is the number you get for maximal disappearance.
- The same comments will apply to NOνA.



K. Abe et al., *Phys. Rev. Lett.* **112**, 181801 (2014)

T2K $\nu_\mu \rightarrow \nu_e$ Oscillation Results

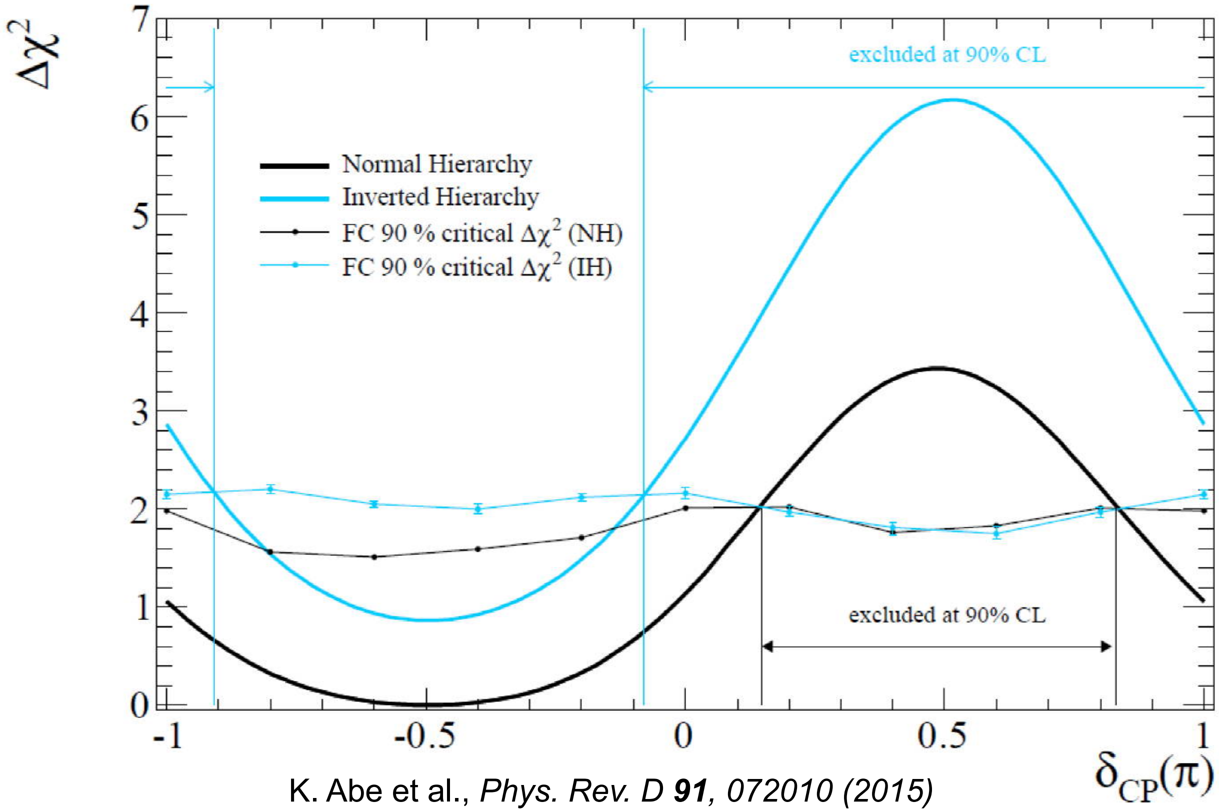
- T2K observed 28 events, including an expected background of 4.9±0.6 events.
- The solid blue line (mine) represents the current reactor average for $\sin^2(2\theta_{13})$.
- The data favor $\delta_{CP} = -\pi/2$, where the NO is 1σ high and the IO is at the 90% C.L.



K. Abe et al., *Phys. Rev. Lett.* **112**, 061802 (2014)

T2K $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- The previous plot was goodness of fit. This plot is the relative likelihood of mass ordering-δ_{CP} combinations.



K. Abe et al., *Phys. Rev. D* **91**, *072010 (2015)*

T2K $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Results

- T2K has been running with horn currents reversed to produce an antineutrino beam, and recently released the first results.
- T2K observed 3 events, including an expected background of 1.8 events. Taking the extremes of mass ordering and δ_{CP}, the expected number of events ranged from 3.7 to 5.5.
- Clear the statistics are insufficient for any conclusion, but since the bi-probability plots are on a negative diagonal, a low antineutrino rate is consistent with a high neutrino rate.

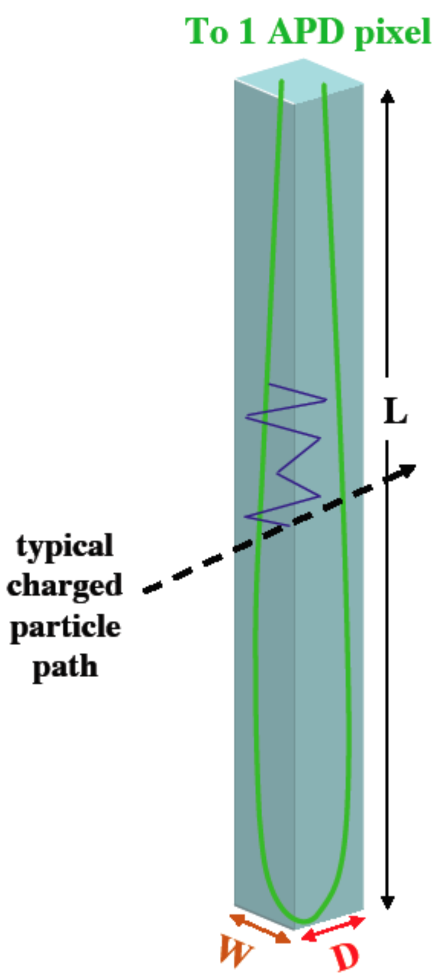
The NOνA Experiment

- The NOνA (NuMI Off-Axis ν_e Appearance Experiment) experiment is the follow-on experiment to MINOS and, as the name implies, optimized for the measurement of $\nu_\mu \rightarrow \nu_e$ oscillations.
- To maximize the matter effect the NOνA far detector is located as far north in the United States as possible.

The NOνA Experiment

- Aspects of the optimization included
  - An off-axis beam
  - Almost 3 times the mass of MINOS
  - An increase in the beam power from 400 kW to 700 kW
  - Almost an order of magnitude finer longitudinal segmentation
  - As much active material as possible, about 63%.

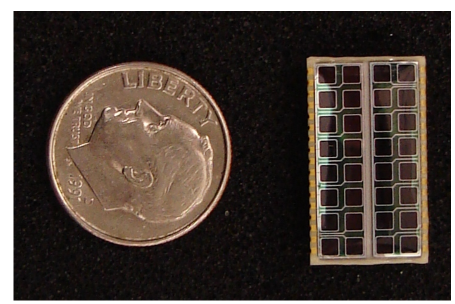
Basic NOνA Detector Element



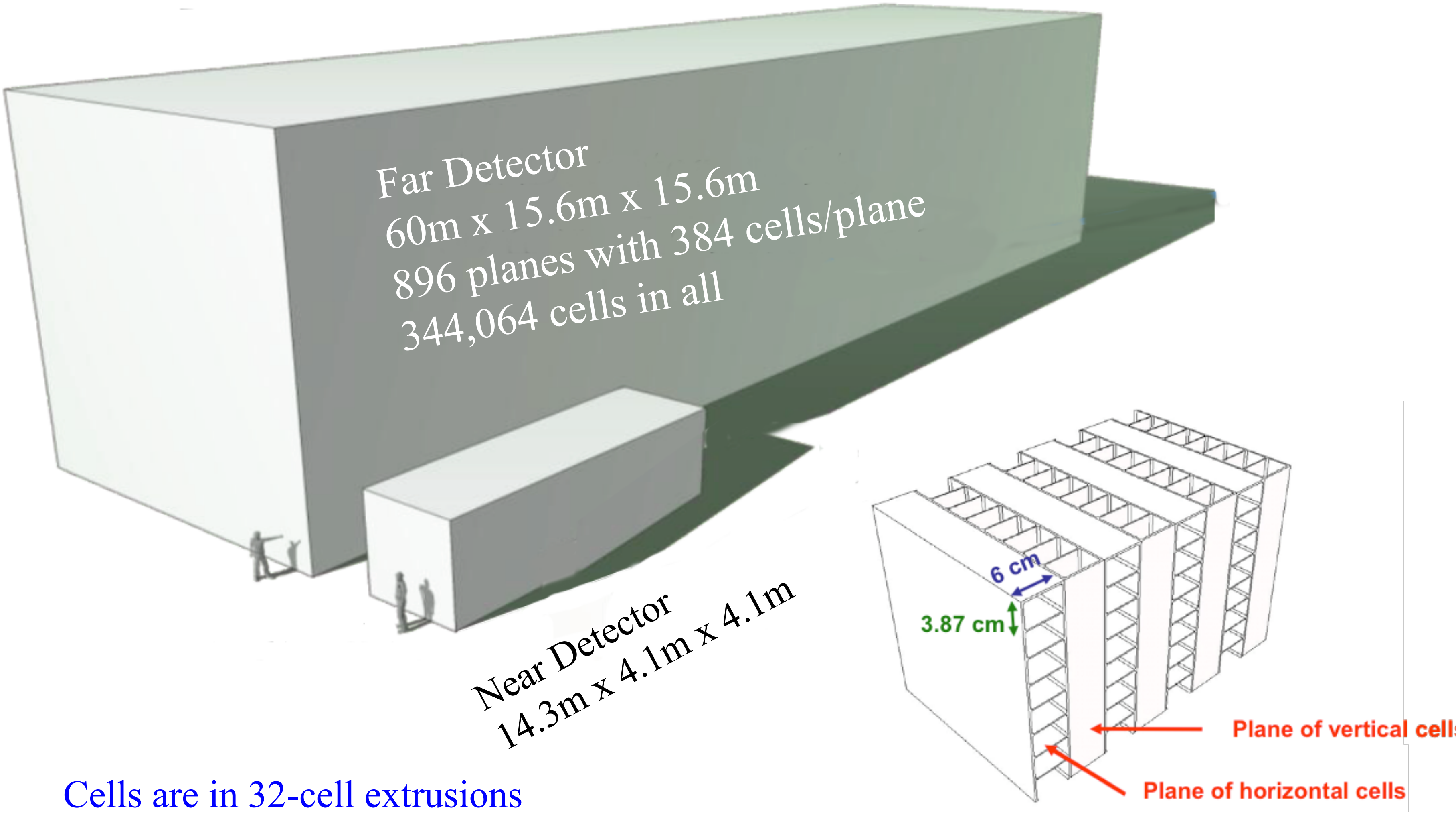
Liquid scintillator in a 4 cm wide, 6 cm deep, 15.6 m long, highly reflective PVC cell.

Light is collected in a U-shaped 0.7 mm wavelength-shifting fiber, both ends of which terminate in a pixel of a 32-pixel avalanche photodiode (APD).

The APD has peak quantum efficiency of 85%. It is run at a gain of 100 and is cooled to -15°C.

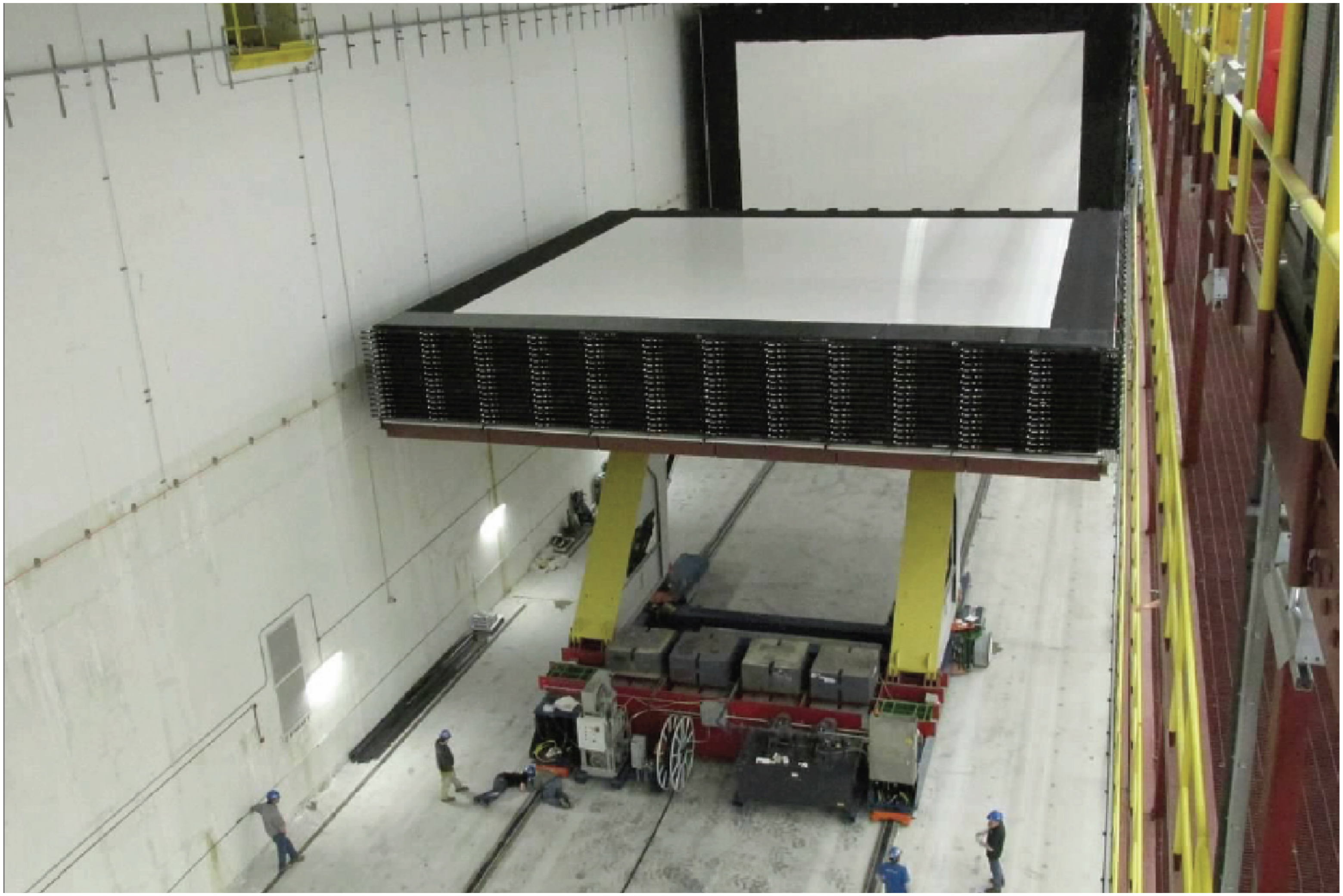


NOνA Detectors



Cells are in 32-cell extrusions

NOvA Far Detector Construction



NOνA Far Detector Top View (~1/3)

NOνA Near Detector

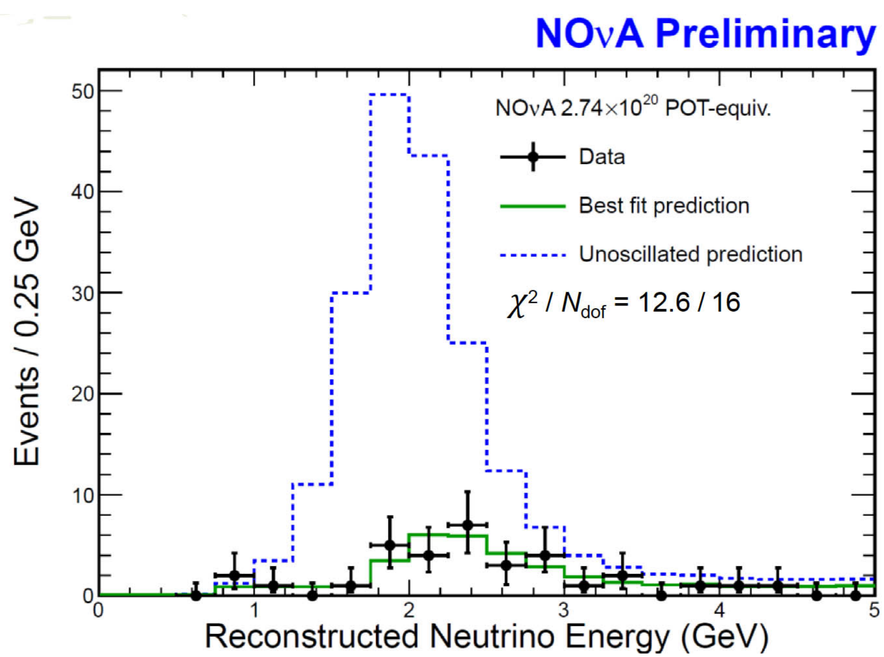
First NOνA Results

- NOνA began taking data on the first 4 kt of the far detector in Feb. 2014 and on the full 14 kt detector in Dec. 2014.
- NOνA released it first results last week on 2.7×10^{20} 14 kt-equivalent protons on target (PoT). NOνA's goal is to achieve 6×10^{20} PoT per year.

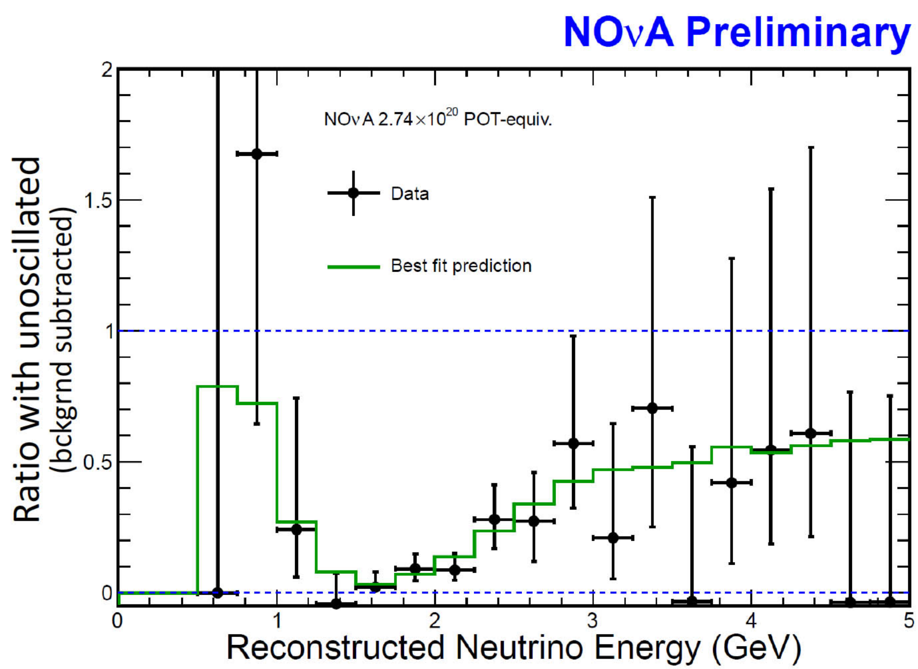
NOνA ν_μ Disappearance Results

- 201 events expected without oscillations
- 33 events seen, including 3.4 background

Energy Spectrum



Survival Probability

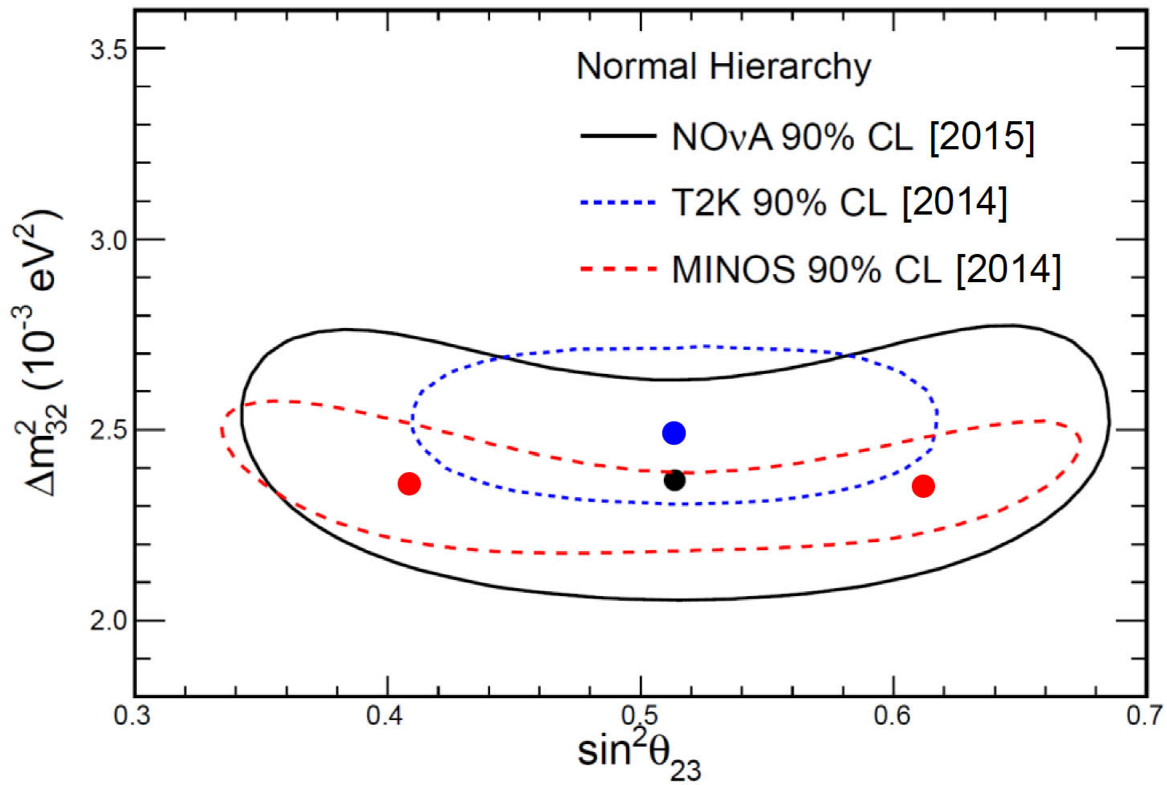


NOvA ν_μ Disappearance Results

$$\Delta m^2_{32} = \begin{cases} (2.37 \pm 0.16) \times 10^{-3}\ \text{eV}^2\ \text{NO} \\ (2.40 \pm 0.17) \times 10^{-3}\ \text{eV}^2\ \text{IO} \end{cases}$$

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

NOvA Preliminary



NOvA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- NOvA has two ν_e selection algorithms.
- The first selection algorithm is a likelihood identifier (LID). LID calculates the likelihood of the transverse and longitudinal profile of the most energetic shower in each event under different particle hypotheses. It then inputs that information along with other kinematic and topological information, such as the shower energy fraction, the energy near the event vertex, shower angle, and the vertex to shower gap, into an artificial neural net.

NOvA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- The second selection algorithm is a library event matching identifier (LEM).
- This is a modification of the algorithm MINOS used in its final analysis.
- LEM compares the signals in each individual cell of an observed event with a library of 77 million simulated events using an electromagnetic analog. Taking the observed event to be positive charges and the library event to be negative charges, the potential energy is calculated. The optimum potential r dependence was found to be $r^{-0.25}$ rather than r^{-1}. The characteristics of the 1000 matches with the lowest potential energy are then fed into an ensemble decision tree.

NOvA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

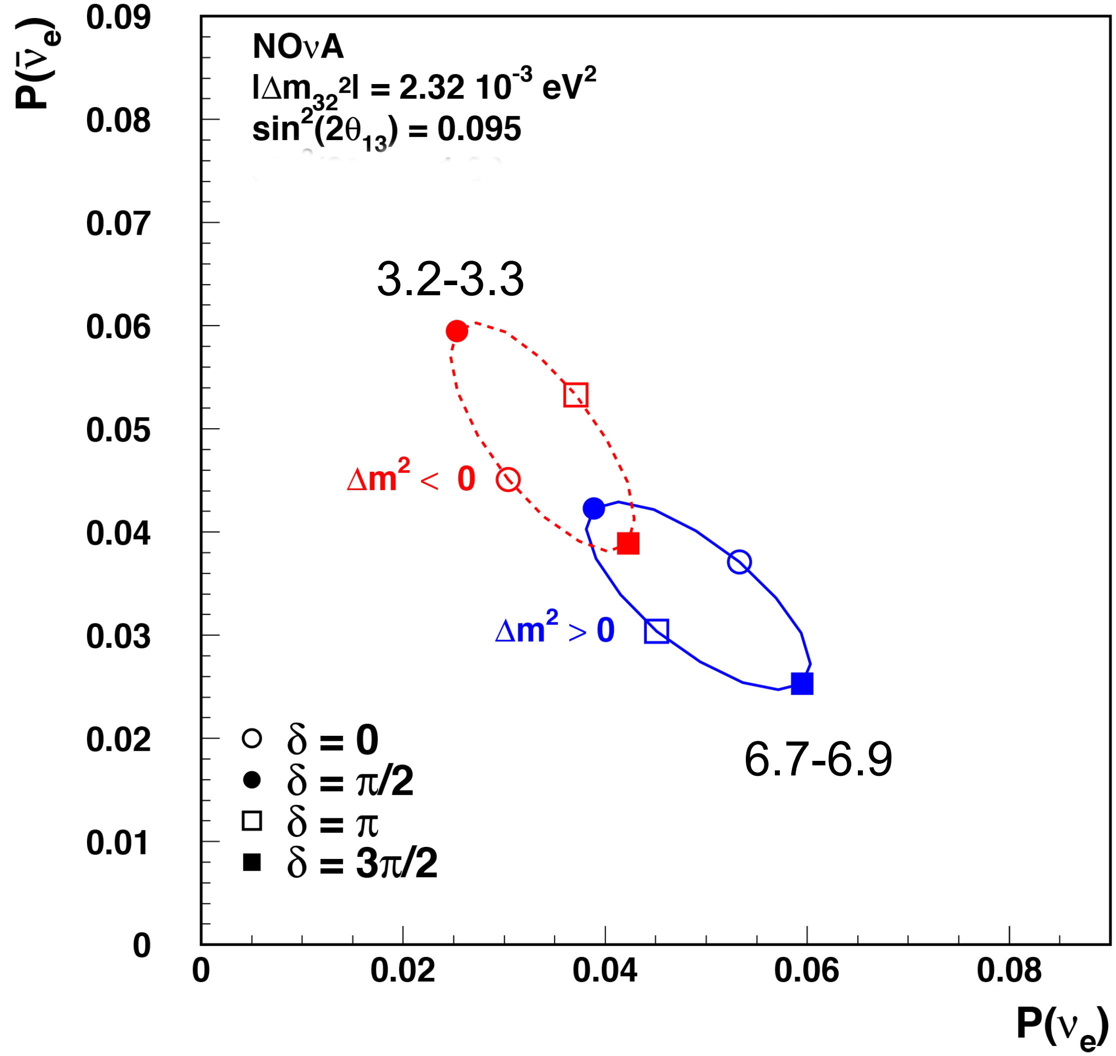
- These to selection algorithms proved to be essentially identical in their selection efficiency and background rejection.
- NOvA does blind analyses, which means that all analysis decisions are made prior to examining the data. It was decided that the results of both selectors would be shown, but that the LID result would be the primary result when a unique answer is required. The basis of this decision was that it is a more common analysis technique, and thus might be easier to explain.

NOvA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

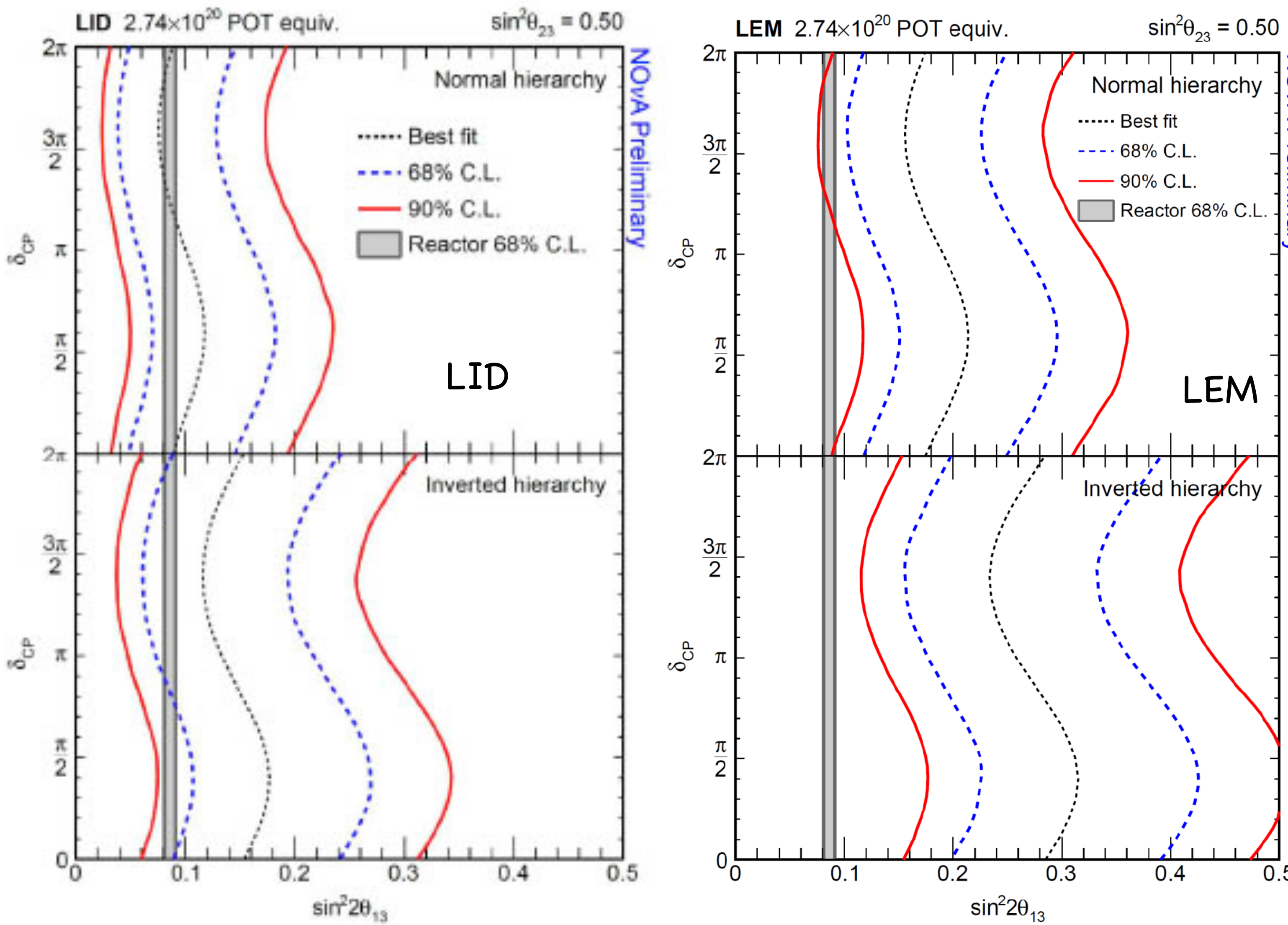
- Upon "opening the box," the LID selector found 6 events, with an expected background of 0.94 ± 0.09 events and LEM selector found 11 events with an expected background of 1.00 ± 0.11 events. All 6 of the LID events were included in the 11 LEM events.
- The expected overlap of signal events between LID and LEM was 62% and the expected overlap of background events was 42%. A calculation of the likelihood of the observed distribution or a less likely distribution using trinomial statistics is 9.2%.

NOνA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- Expected number of events (including background) at the two extremes of the bi-probability plot for maximal mixing: LID-LEM

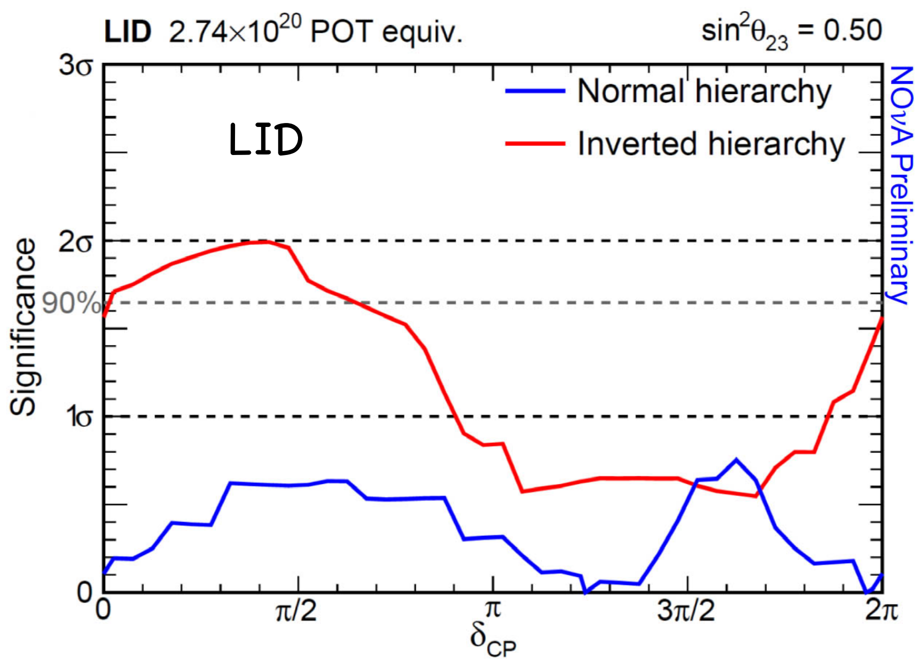


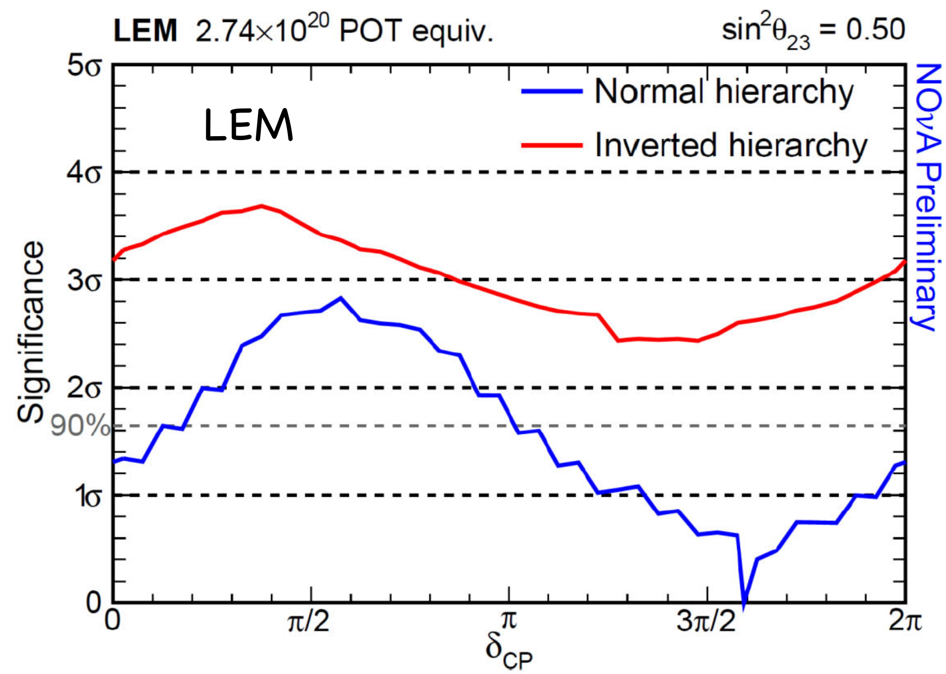
NOνA $\nu_\mu \rightarrow \nu_e$ Oscillation Results



NOνA $\nu_\mu \rightarrow \nu_e$ Oscillation Results

- The previous plots were goodness of fit. These plots are relative likelihoods of mass ordering-δ_{CP} combinations. They are bumpy due to the discreteness of the data.

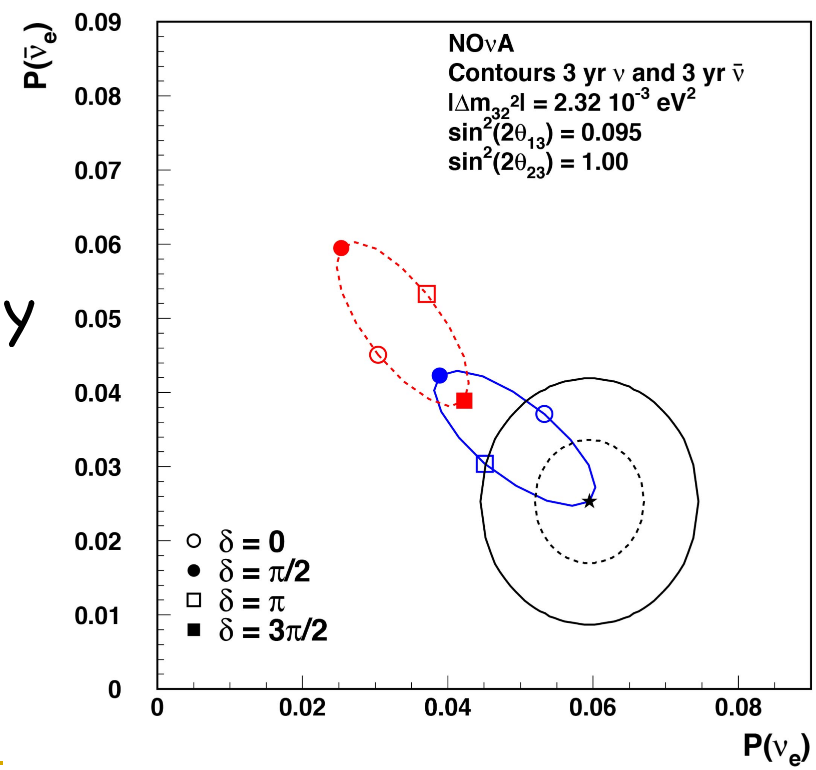




NOνA 6-year Sensitivity

- Both T2K and NOνA are hinting that the ultimate result could be what is a sweet spot for NOνA: Normal mass ordering and $\delta_{CP} = 3\pi/2$. The plot shows NOνA's 1 and 2 σ sensitivity for 3 years of neutrino and 3 years of antineutrino running. (NOνA will probably run longer.)

1 and 2 σ Contours for Starred Point



NOνA's Plans

- There is no firm decision, but a reasonable plan would be to continue running on neutrinos until the internal data cutoff for Neutrino 2016 and then switch to antineutrino running.
- The anticipation is that NuMI would reach its design power by early 2016 and that NOνA would triple the present data by Neutrino 2016.