NOνA Beam Requirements

SNuMI Meeting

Fermilab

16 October 2006

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NOνA:

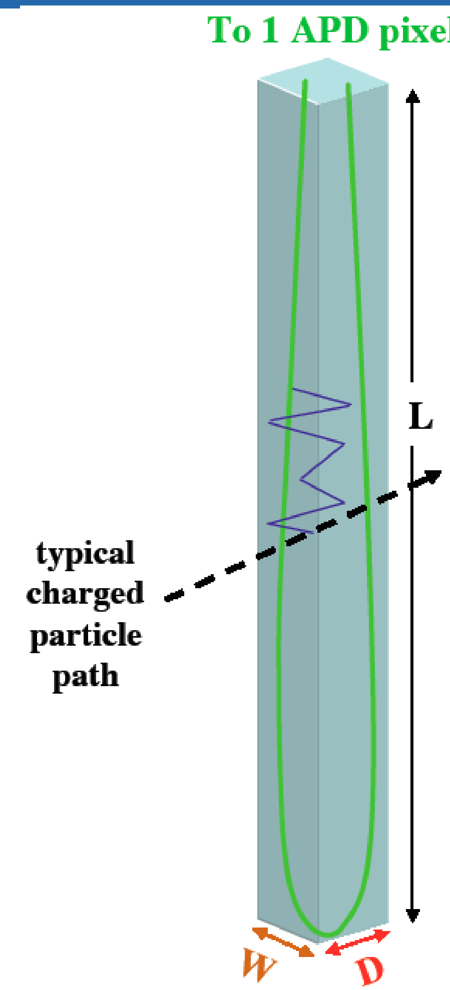
NuMI Off-Axis ν_e Appearance Experiment

- NOνA is a proposed 2nd generation experiment on the NuMI beamline.
- Its main physics goal will be the study of $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric oscillation length. It will improve MINOS's capability for this study by approximately an order of magnitude.
- The Far Detector will be located near Ash River, MN, 810 km from Fermilab and 12 km off the center of the NuMI beamline.
  - The unique characteristic of NOνA is its long baseline, which allows access to matter effects, which can be used to determine the ordering of the neutrino mass states. The Ash River site provides the longest baseline that is still in the U.S.
  - The off-axis location provides a narrow-band beam about the oscillation maximum. This maximizes the relevant flux and decreases the background.

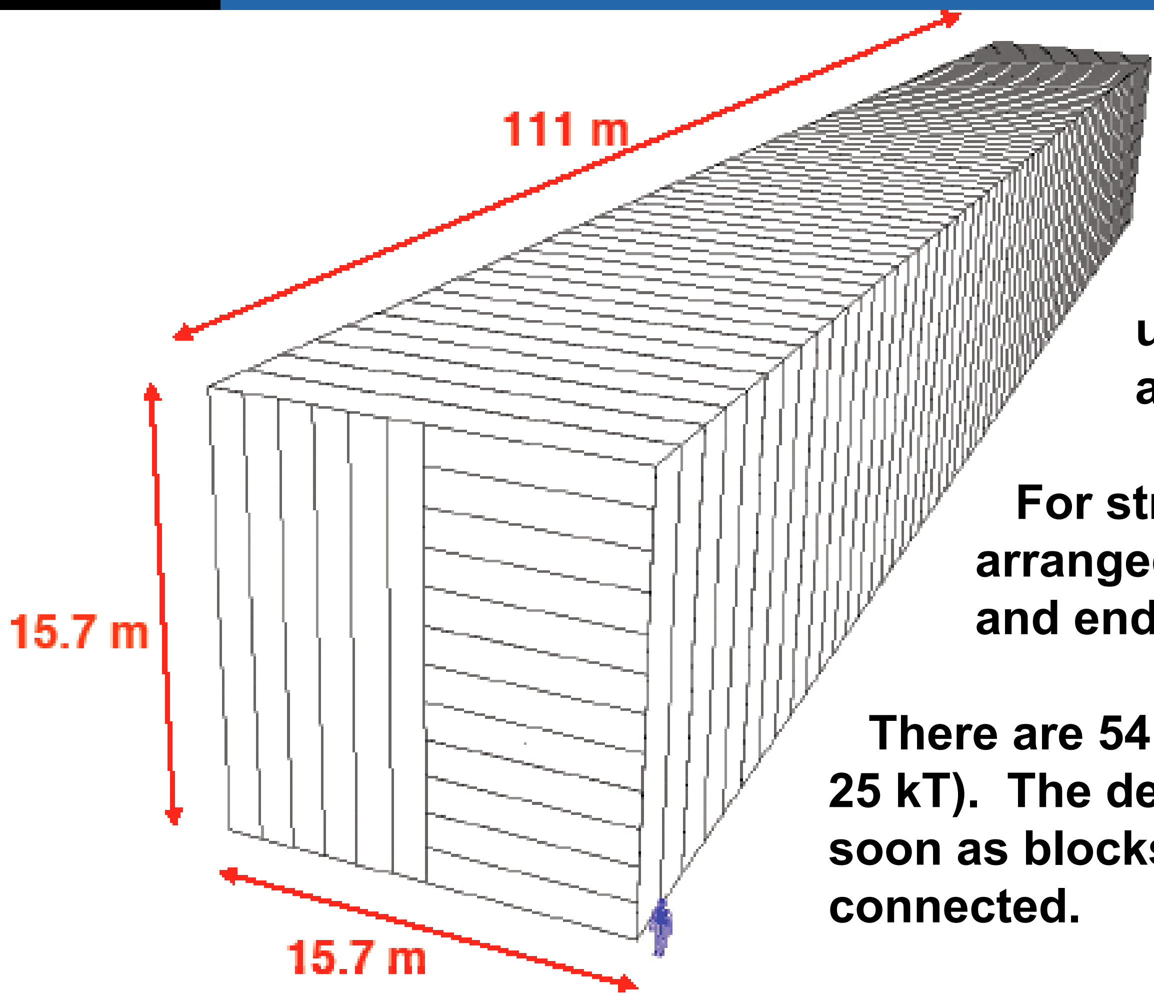
NOνA:

NuMI Off-Axis ν_e Appearance Experiment

- We will baseline the Far Detector at 20 kT, although we hope to expand it to 25 kT through earned contingency and foreign contributions.
- The Far Detector will be a totally active, tracking liquid scintillator calorimeter.
- The basic detector element is liquid scintillator contained in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell. The cell is readout through a wavelength-shifting fiber into an APD.
- This gives a longitudinal sampling of 0.15 radiation lengths compared to 1.5 radiation lengths for MINOS.



The Far Detector



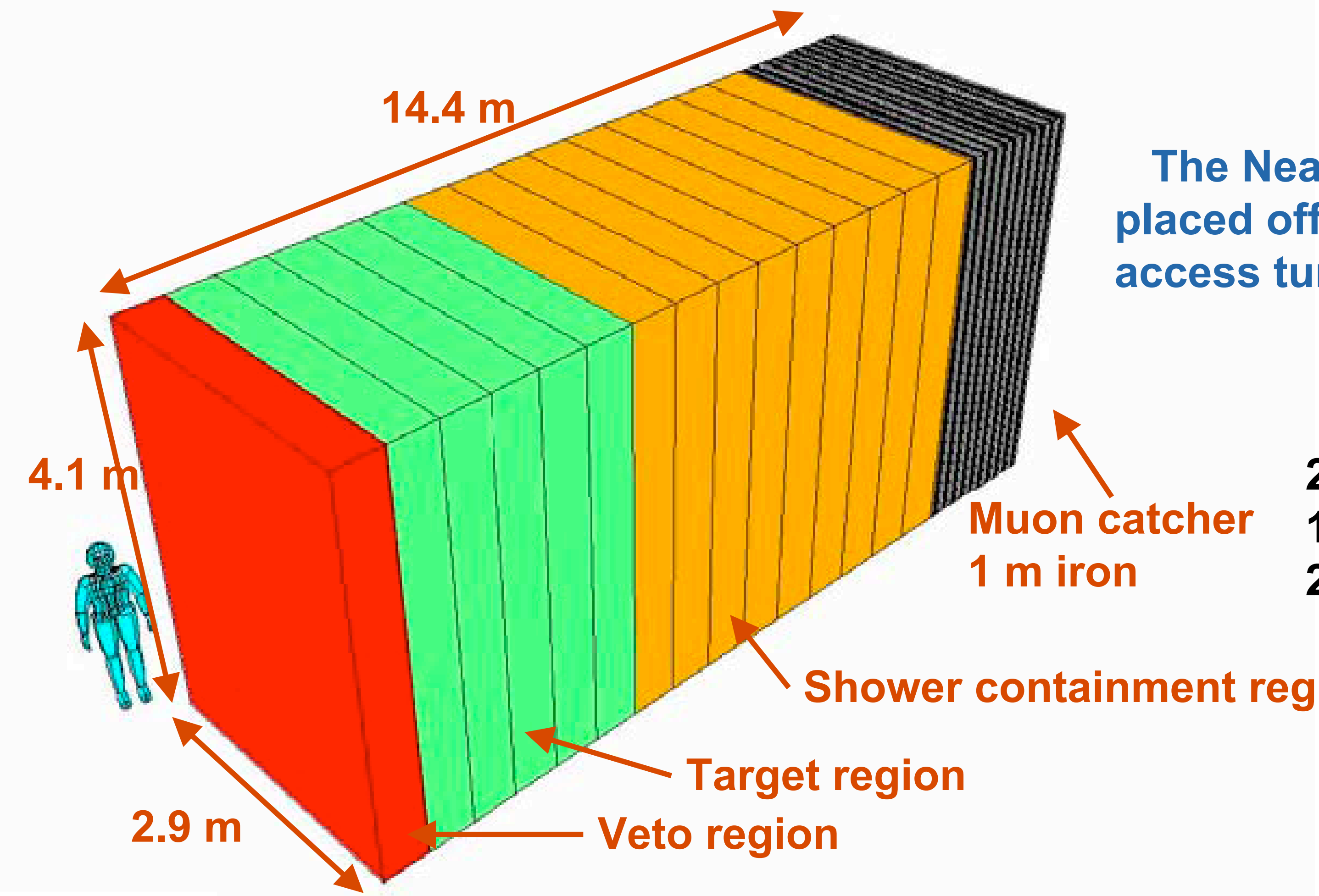
The cells are made from 32-cell extrusions.

12 extrusion modules make up a plane. The planes alternate horizontal and vertical.

For structural reasons, the planes are arranged in 31-plane blocks, beginning and ending in a vertical plane.

There are 54 blocks = 1654 planes (for 25 kT). The detector can start taking data as soon as blocks are filled and the electronics connected.

The Near Detector



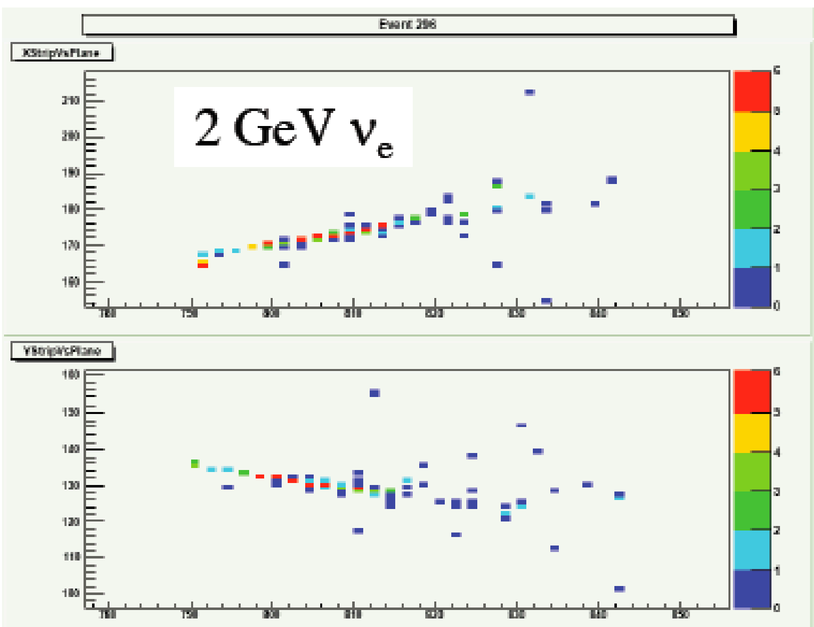
The Near Detector will be placed off-axis in the MINOS access tunnel.

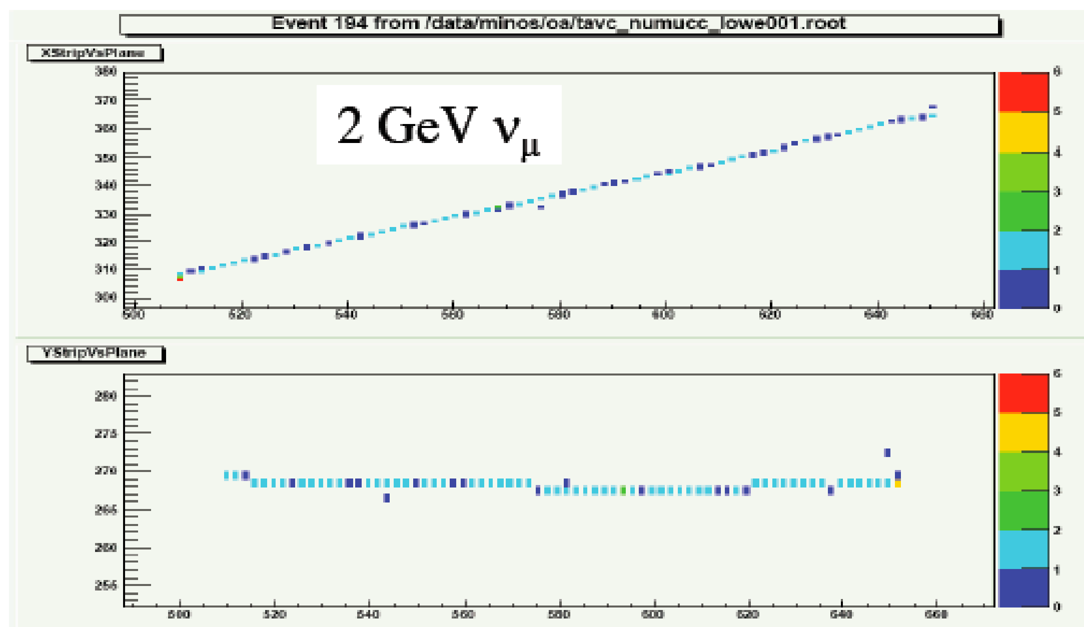
209 T
126 T totally active
23 T fiducial

Event Quality

Longitudinal sampling is 0.15 X0, which gives excellent μ-e separation.

A 2-GeV muon is 60 planes long.





Neutrino Oscillations

- Neutrino oscillations occur because the weak eigenstates and not identical to the mass eigenstates.
- The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix

- The mixing matrix can be specified by 3 angles and one complex phase:

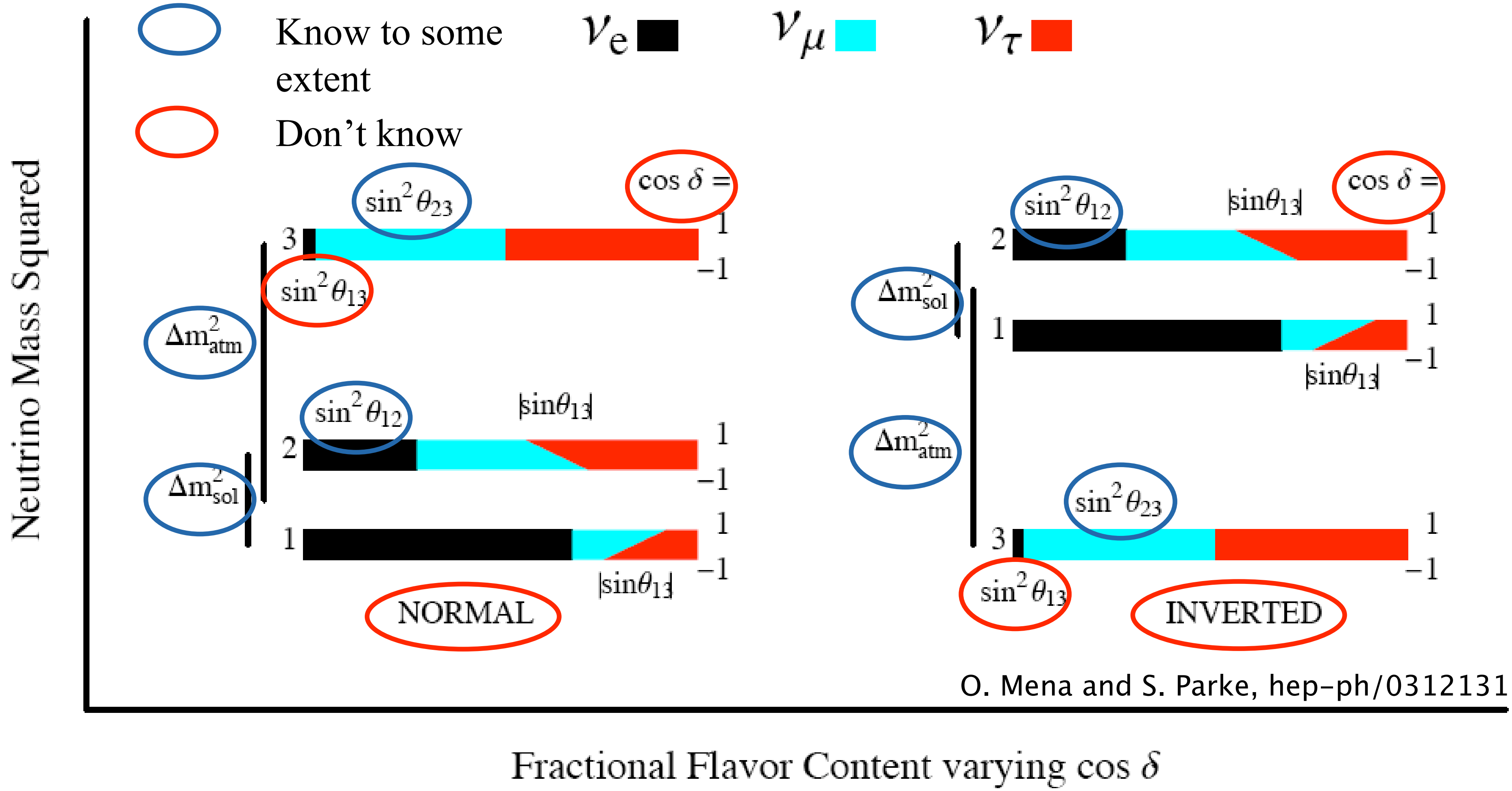
$$\left|\nu_l\right\rangle = U\left|\nu_n\right\rangle, \quad \text{where} \quad (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric $\nu_\mu \leftrightarrow \nu_\tau$ | Atmospheric $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$ | Solar

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

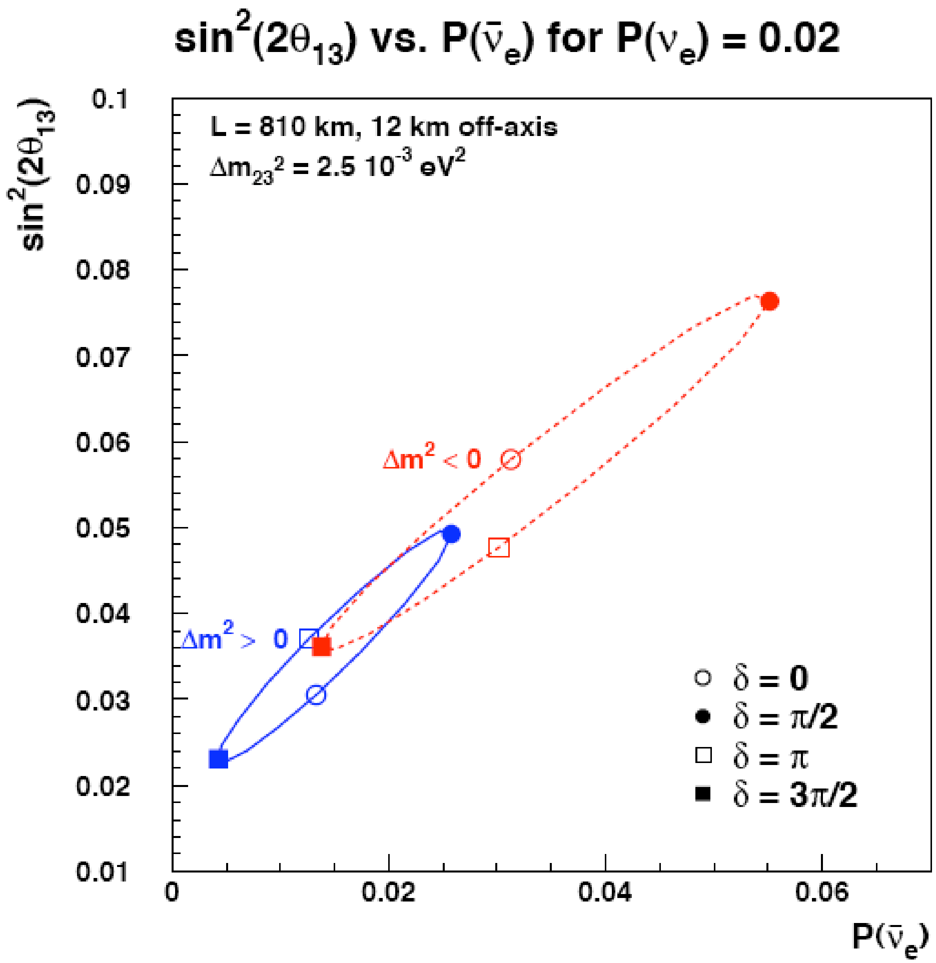
What We Know and What We Don't Know



How Do We Measure These Parameters?

- $\sin^2(2\theta_{13})$ is measured by the rate of the sum of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. (Slight oversimplification)
- Both the CP-violating phase δ and the mass ordering are both measured by the difference between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.
- The mass ordering is only sensitive to a coherent interaction between ν_e's and electrons in the earth. It is significant only for long-baseline experiments, such as NOνA. (It is a false CP-violating effect due to the presence of electrons and not positrons in the earth.)

Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation



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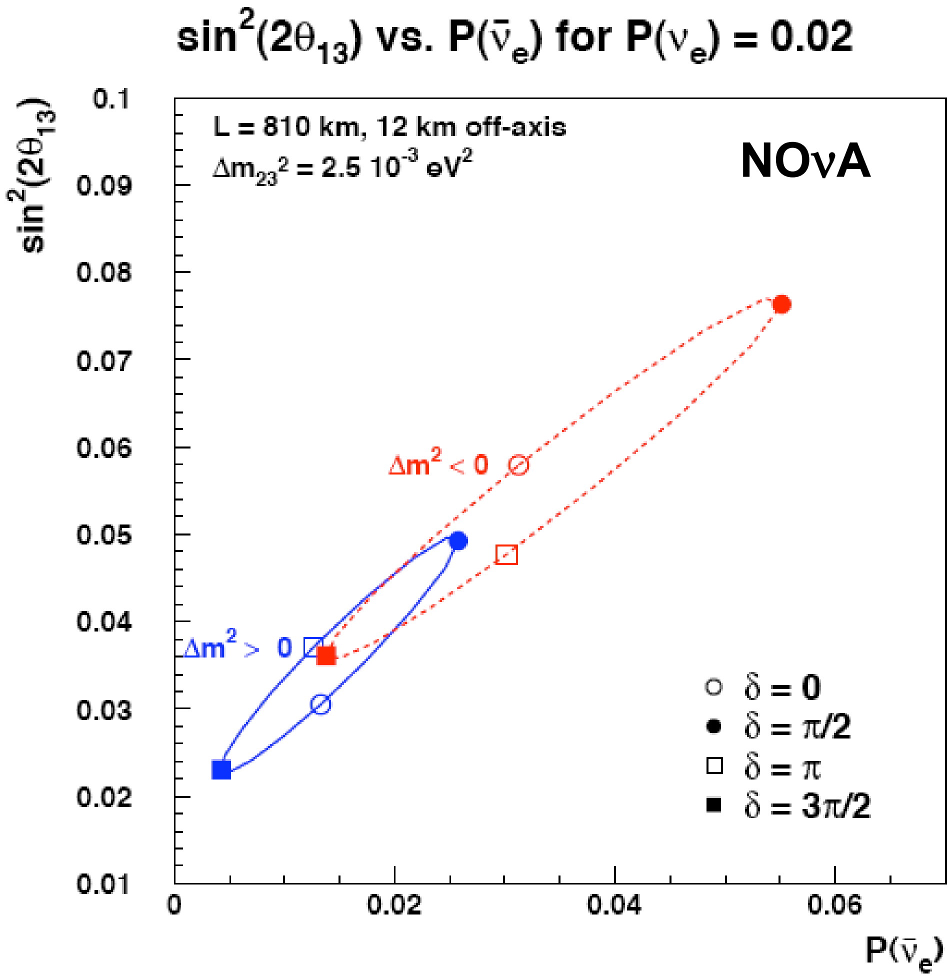
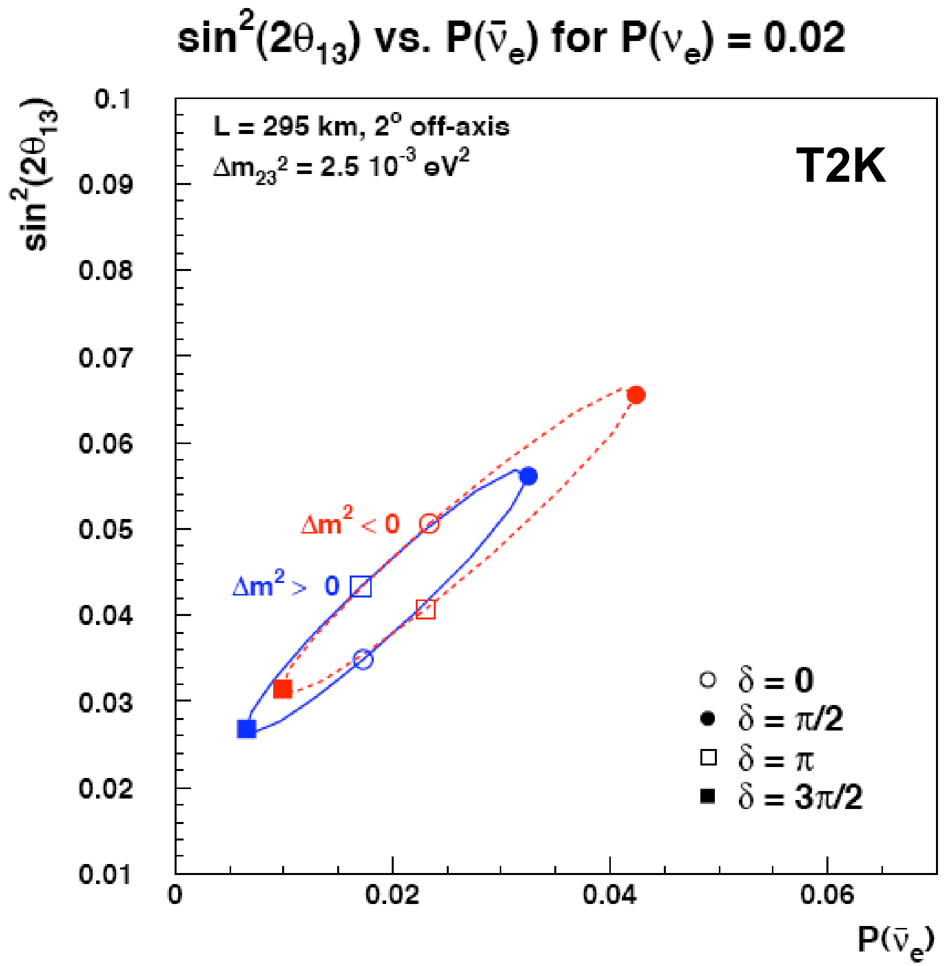
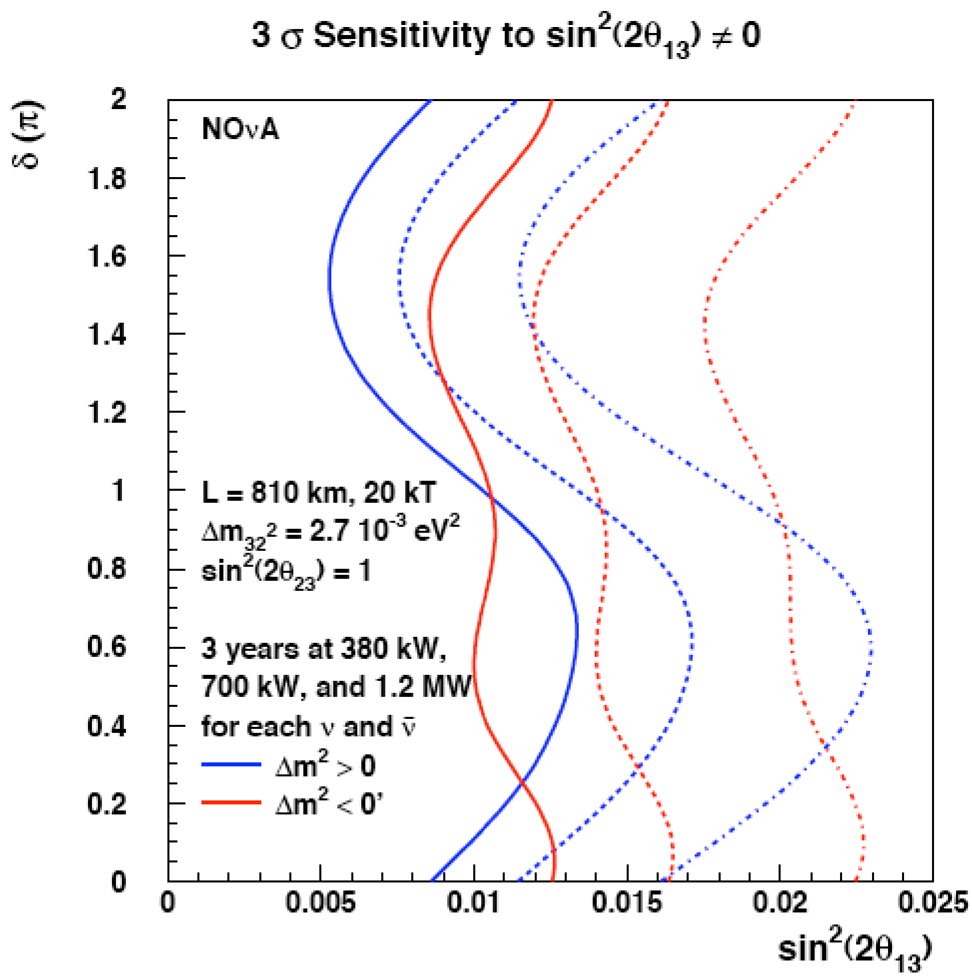




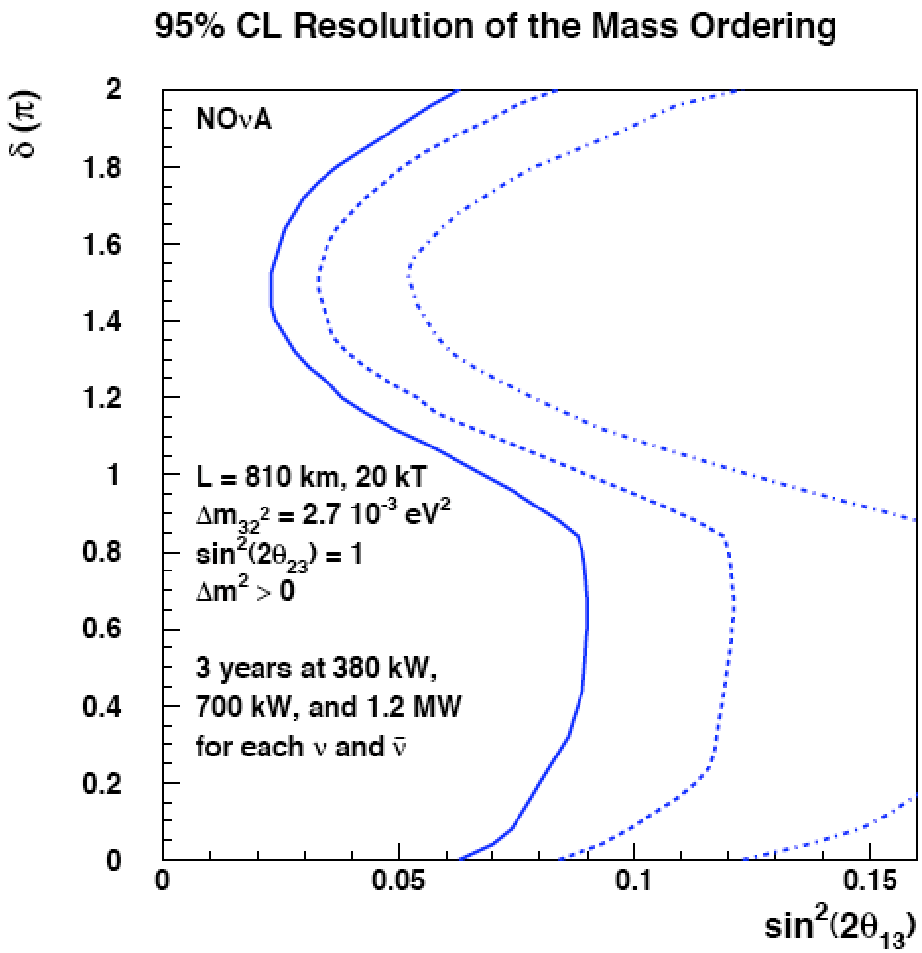
3 σ Sensitivity to $\theta_{13} \neq 0$

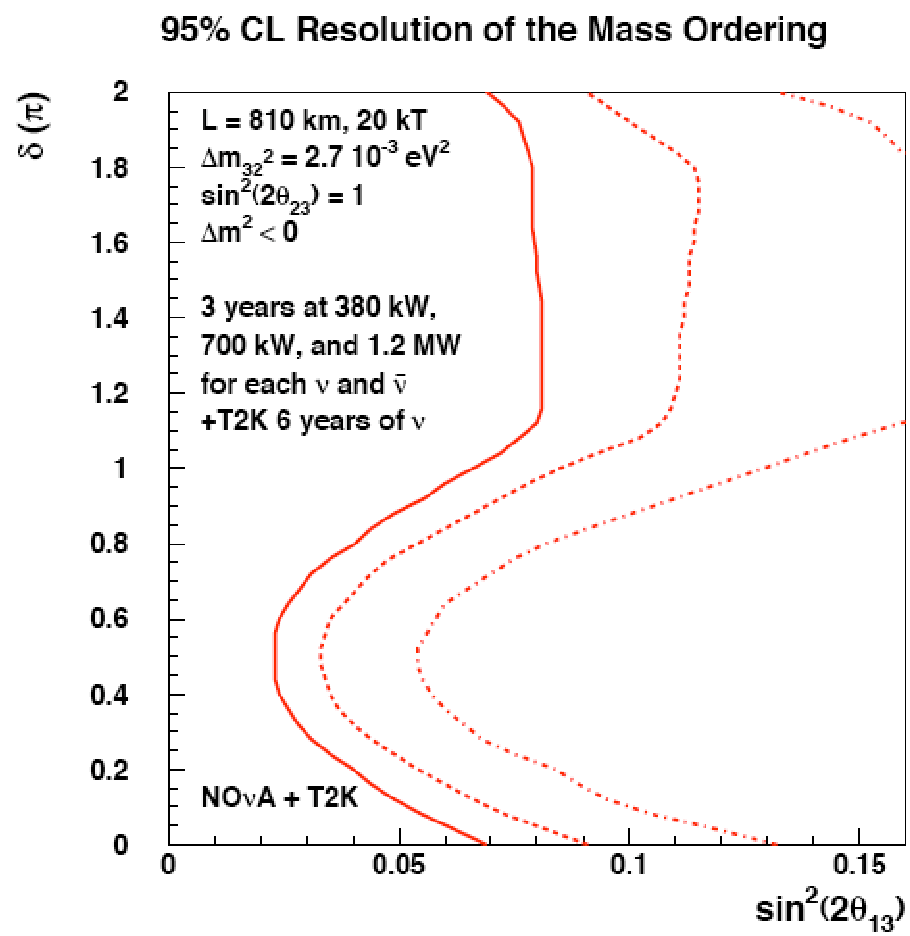


Importance of the Mass Ordering

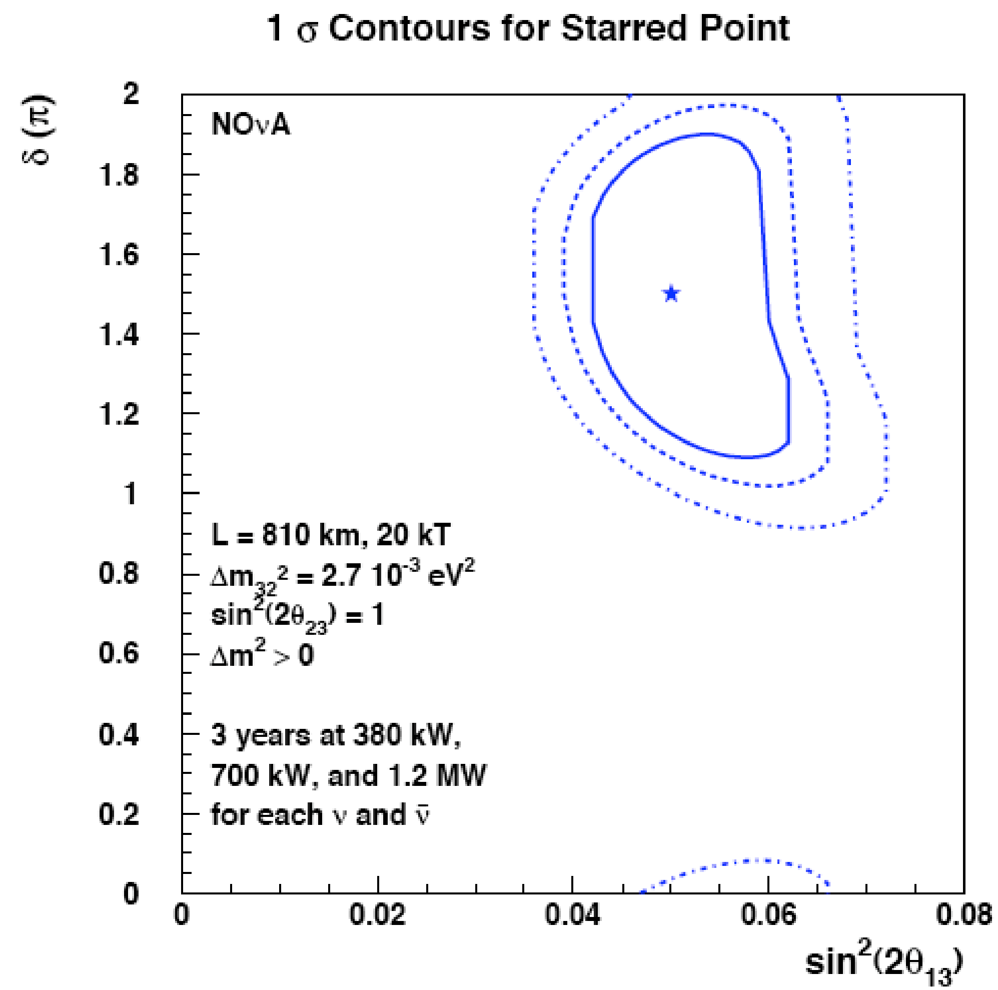
- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

95% CL Resolution of the Mass Ordering





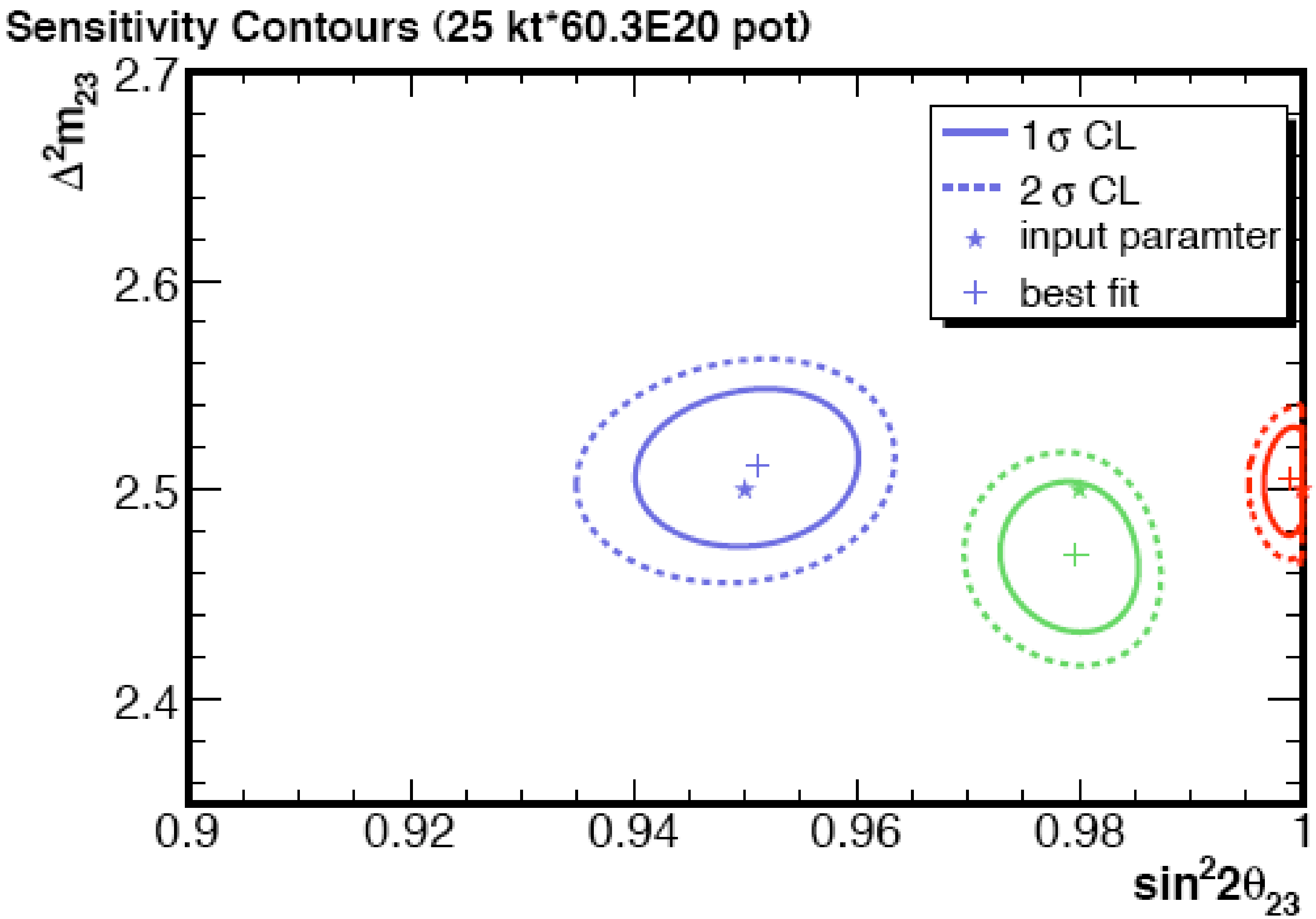
δ vs. $\sin^2(2\theta_{13})$ Contours



Measurement of $\sin^2(2\theta_{23})$

- **Whether the atmospheric mixing is maximal is an important question both practically (comparison of reactor and accelerator measurements) and theoretically (Is there a symmetry that induces maximal mixing?).**
- **The combination of the narrow-band beam and NOνA's excellent energy resolution allows it to do a high-precision measurement of $\sin^2(2\theta_{23})$ by measuring quasielastic ν_μ CC events. (Again, about an order of magnitude more precisely than MINOS.)**

Measurement of $\sin^2(2\theta_{23})$



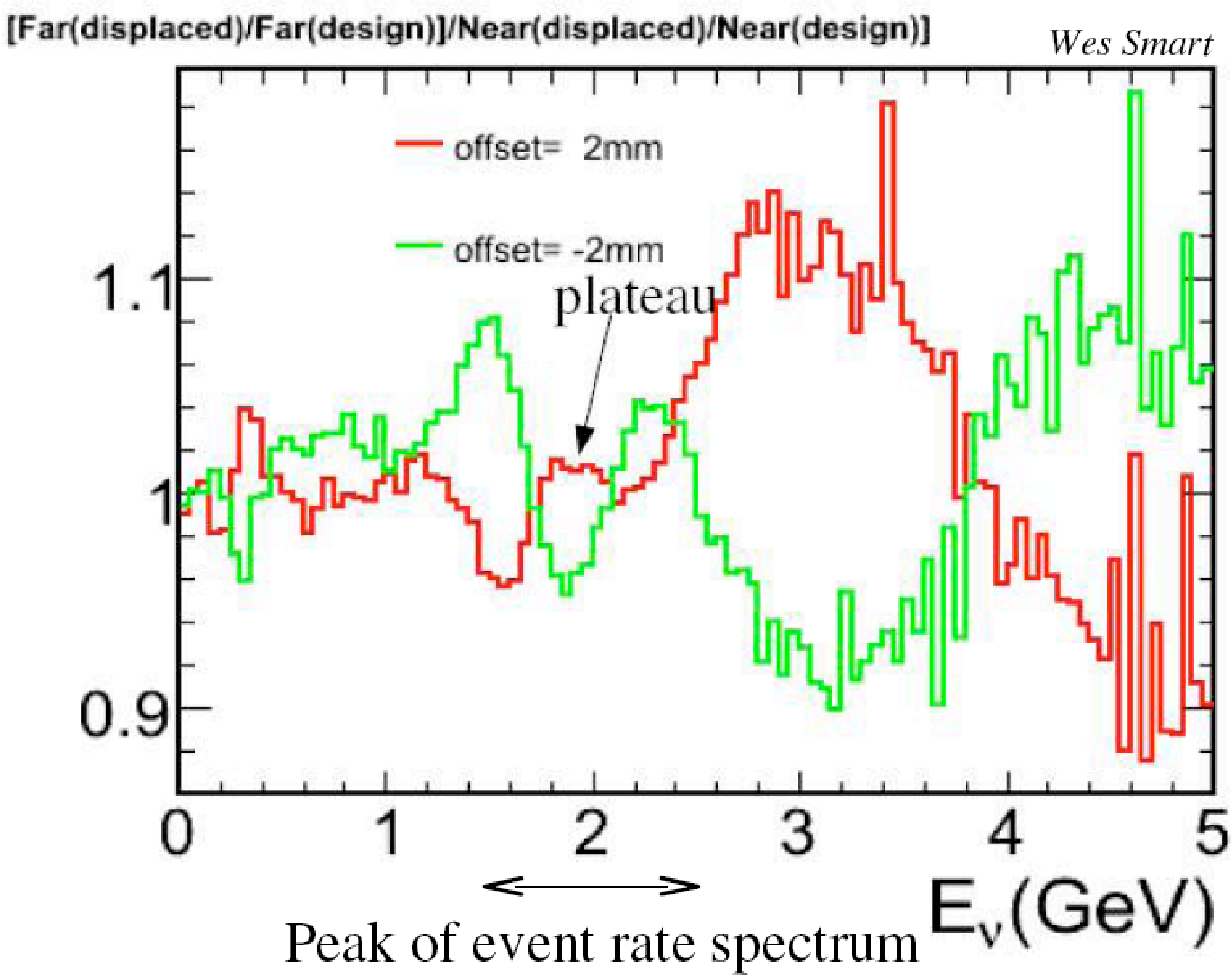
If $\sin^2(2\theta_{23})$ = 1, then it can be measured to 0.004.

Otherwise, it can be measured to ~0.01.

Horn Alignment Requirements

- Wes Smart and Zarko Pavlovic calculated ν_μ fluxes for various shifts in positions of beam components. These can be used to estimate our sensitivity to misalignments for the ν_e appearance measurements.
- Tingjun Yang used these calculations to study the effect of misalignments on the ν_μ disappearance measurements.
- NOνA is most sensitive to horn 1 shifts along the horizontal direction, since these effectively change the off-axis angle.

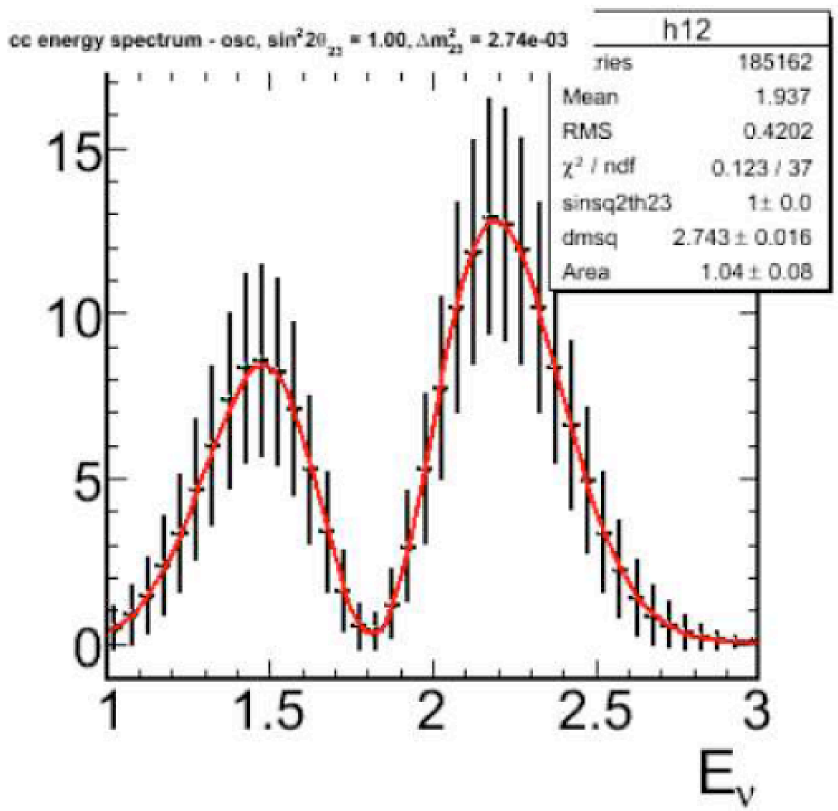
Changes in Near/Far Ratio by ± 2 mm Horn 1 Shift

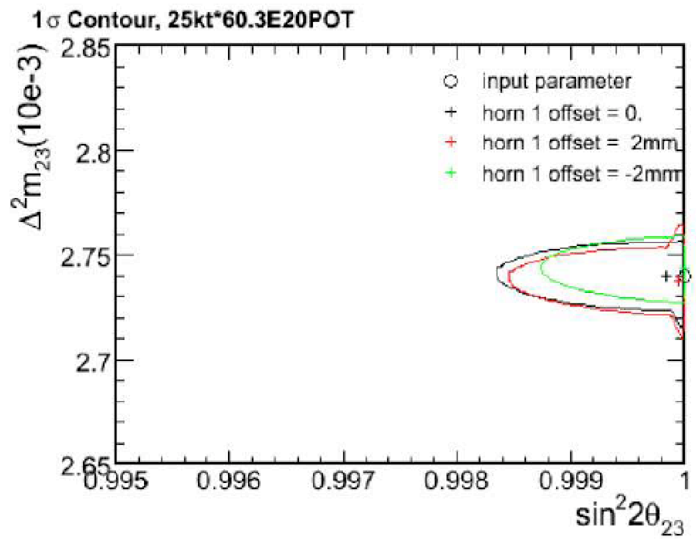


Integral changes by 0.2% for +2 mm and by 0.8% for -2 mm.

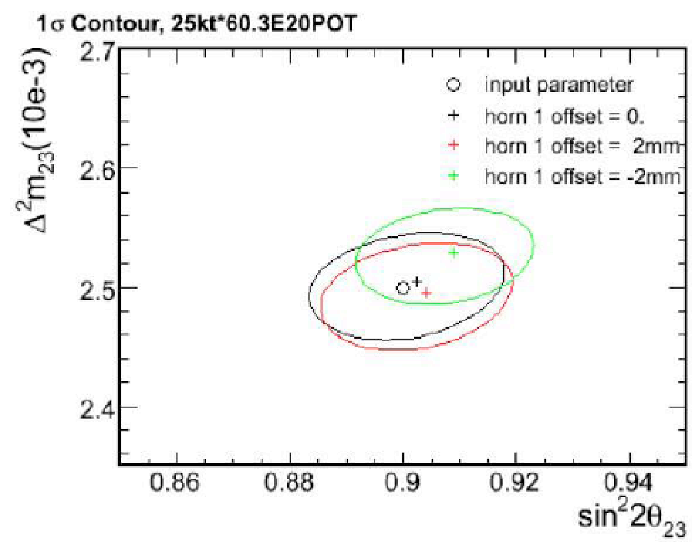
Changes in ν_μ Disappearance by ± 2 mm Horn 1 Shift

ν_μ CC-QE spectrum for (1.0, 2.7x10^{-3} eV^2)





Maximum bias ~1%



Conclusions

- NOνA is statistics limited.
- The most cost-effective way of providing higher statistics is through beam intensity improvements.
- The proposed 1.5 mm beam alignment tolerance appears adequate for NOνA's needs.