The NOνA Electron-Neutrino Appearance Experiment

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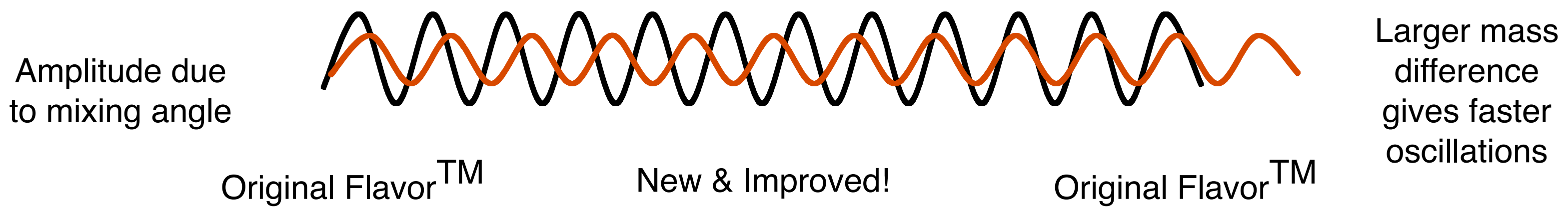
Fermilab

Outline

- Neutrino Oscillations
- Physics Goals of NOvA
- NOvA Design
- NOvA Physics Reach
- Status of NOvA

Reminder: Neutrino Mixing



- Neutrino flavor eigenstates (e,μ,τ) are different from the mass eigenstates (1,2,3)
- Neutrinos produced by weak interactions in a given flavor state can transform as they travel.

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

Neutrino Mixing Matrix (aka MNSP Matrix)

- Oscillation prob is a function of the energy of neutrino and distance travelled, and is parameterized by U_{ij} and $\Delta m^2_{ij} \equiv m^2_i - m^2_j$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin^2[1.27 \Delta m^2_{ij} (L/E)]$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin^2[2.54 \Delta m^2_{ij} (L/E)]$$

L in km,
E in GeV

Mixing Matrix

Atmospheric

CP-violating Phase & Cross terms

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

Solar/ KamLAND

Majorana CP-violating phases

$$\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\text{where } c_{ij} \equiv cos(\theta_{ij}) \text{ and } s_{ij} \equiv sin(\theta_{ij})$$

- Atmospheric neutrinos in Super-K and accelerator neutrinos in K2K (and now MINOS) have measured $|\Delta m_{23}^2|$ and $\sin^2 2\theta_{23}$
- Solar neutrinos in Homestake, Gallex, SAGE, GNO, Kamiokande, Super-Kamiokande, and SNO, plus the reactor anti-neutrinos in KamLAND determine Δm_{12}^2 and $\sin^2 2\theta_{12}$
- No measurements of θ_{13} or the CP phase(s)
- Best limit on $\sin^2 2\theta_{13}$ is < 0.18 from CHOOZ (for $|\Delta m^2_{23}|=2.0\text{x}10^{-3}\text{eV}^2$)

Oscillations in Matter - The MSW Effect

- Matter affects oscillations
  - All neutrinos can scatter off electrons in matter via exchange of a Z boson
  - Electron neutrinos can also exchange a W boson
- For constant matter densities, for two flavor oscillations, the expression is modified by:

$$\Delta m_M^2 \equiv \Delta m^2 \sqrt{sin^2 2\theta + (cos^2\theta - x)^2}$$

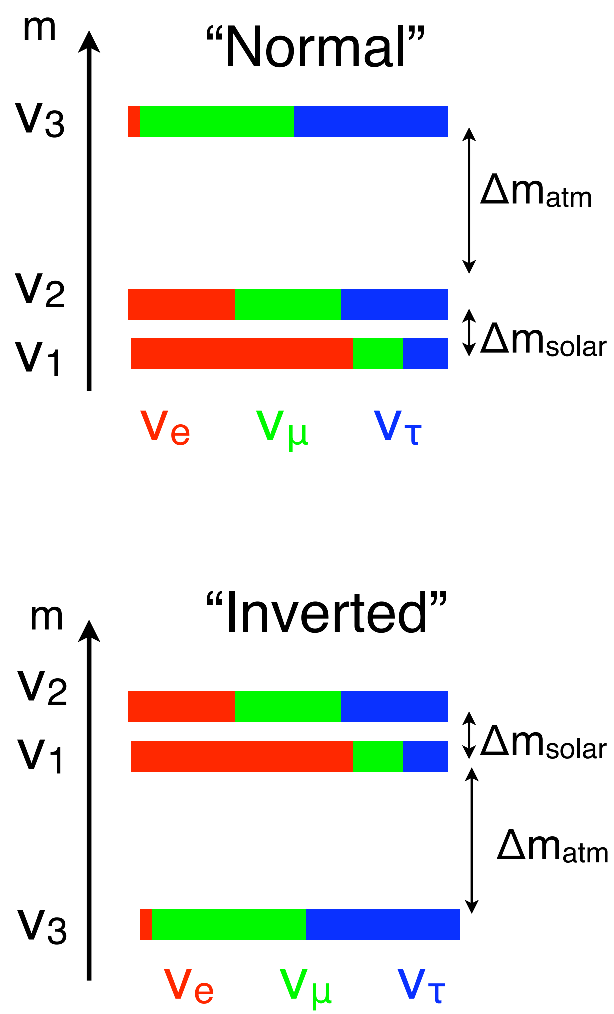
$$sin^2 2\theta_M \equiv \frac{sin^2 2\theta}{sin^2 2\theta + (cos^2\theta - x)^2}$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

- No additional free parameters
- Depends on electron density in matter
- Note that change depends on x, and therefore on the sign of Δm^2.
- Sign of x flips for anti-neutrinos.

Important Questions about Mixing

- Is $\sin^2 2\theta_{23} = 1$ ($\theta_{23}=45^o$)?
  - Could be a symmetry in nature
- How large is θ_{13}?
- Is there CP violation?
  - Can only see it if all θ_{ij} are !=0
- Is the mass hierarchy "normal" or "inverted"?
  - The solar neutrino results, from the large matter effects in the Sun, have told us that $m_1<m_2$
  - Matter effects on electron neutrino appearance in long baseline neutrino beams can help us determine if $m_3<m_2$

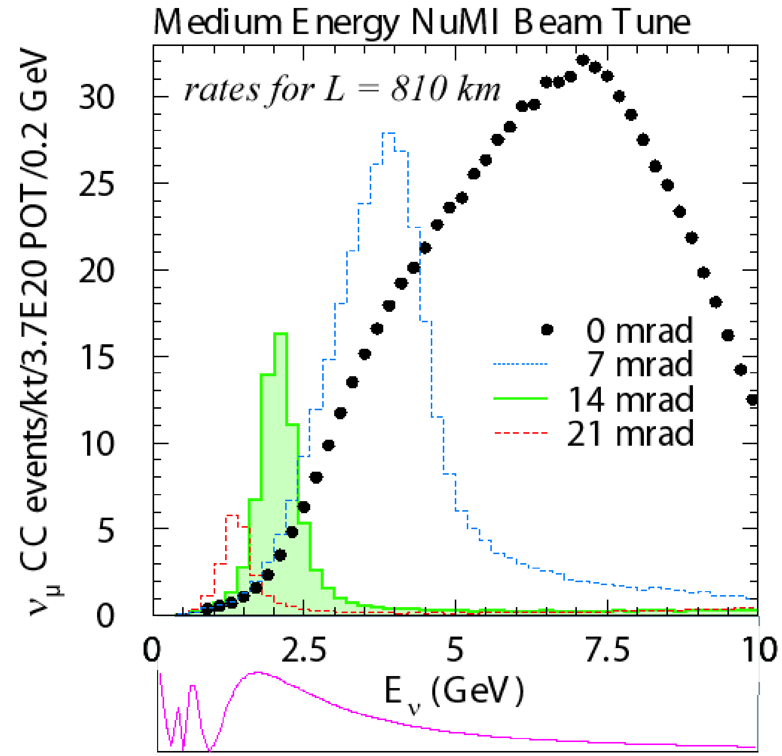


NOνA Physics Goals

- Establish $\nu_\mu \to \nu_e$ oscillations at the atmospheric length scale, for $\sin^2 2\theta_{13}$ >~0.01
  - Look for the appearance of electron neutrinos
- Precision measurement of θ_{23} (to 1%)
  - Measure the disappearance of muon neutrinos
- Study matter effects in the earth over a long baseline to probe the order of the mass hierarchy
  - Look for differences in ν_μ vs anti-ν_μ oscillations
- Study CP violation in neutrinos

NOνA Overview

- NuMI Off-Axis ν_e Appearance Experiment
- Will use the NuMI neutrino beam, produced at Fermilab
- Will place the detector off-axis of the neutrino beam
    - Higher flux at oscillation max
    - Narrow energy-band, lower backgrounds from high-energy tail
- Near detector at Fermilab, ~1 km from target, 0.02 kton fiducial
- Far detector in northern MN, 15 mrad off-axis (12 km), ~800 km away, 25 kton

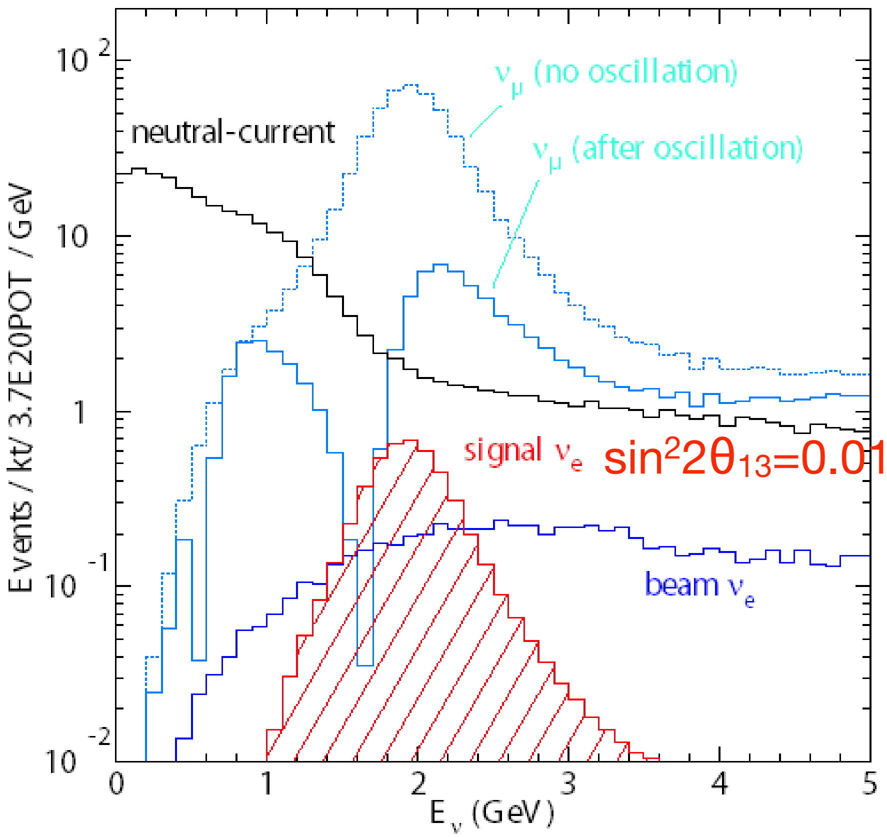


Oscillation prob, L=810 km, Δm^2_{23}=0.0025 eV^2

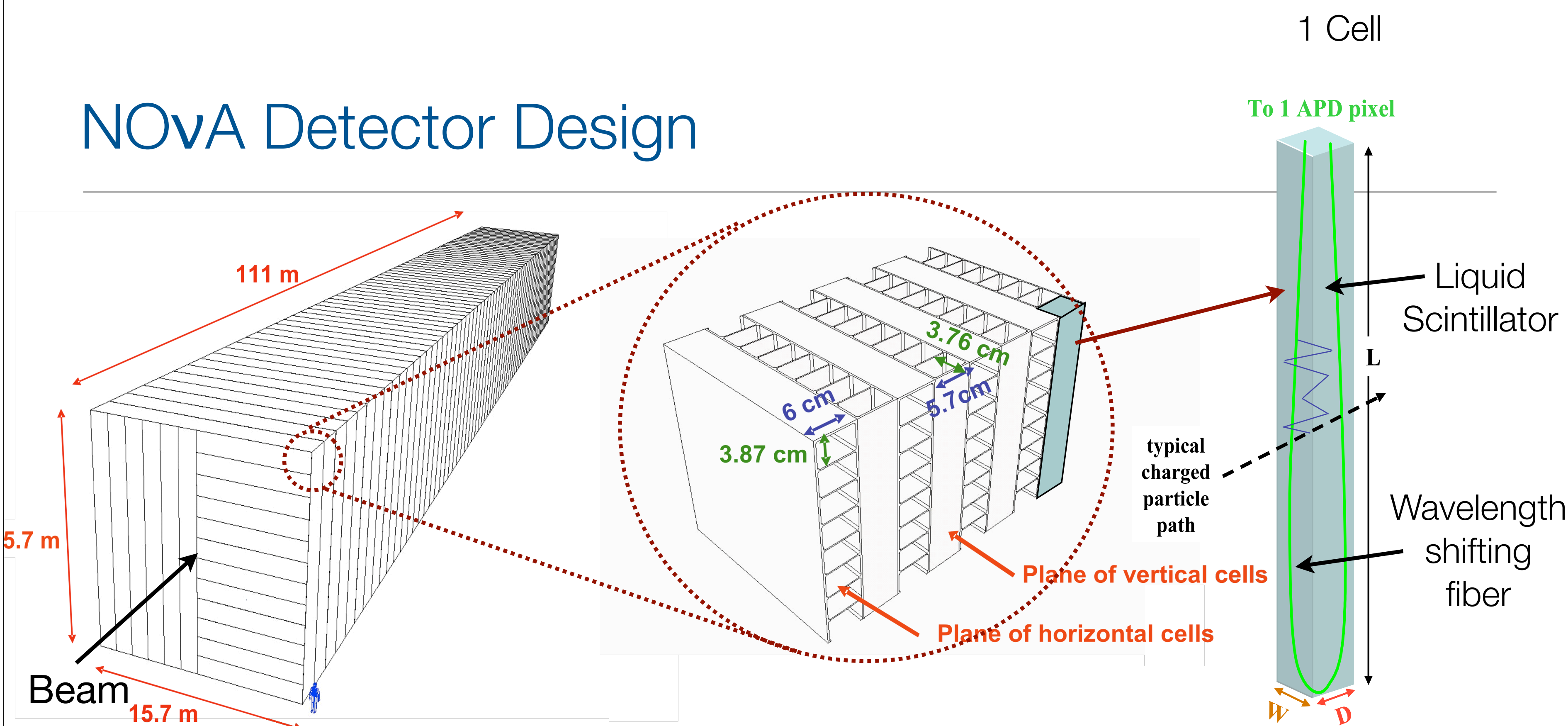
NOvA Detector Requirements

- To be sensitive to ν_e appearance down to $\sin^2 2\theta_{13}=0.01$, the detector must:
  - See dozens of ν_e events. Requires a mass of tens of kilotons
  - Have 100:1 rejection of neutral-current events. This requires a high degree of granularity
  - Have good energy resolution to reject many of the beam ν_e events. This requires a large fraction of the detector to be optically active and good light collection.

Event Rates



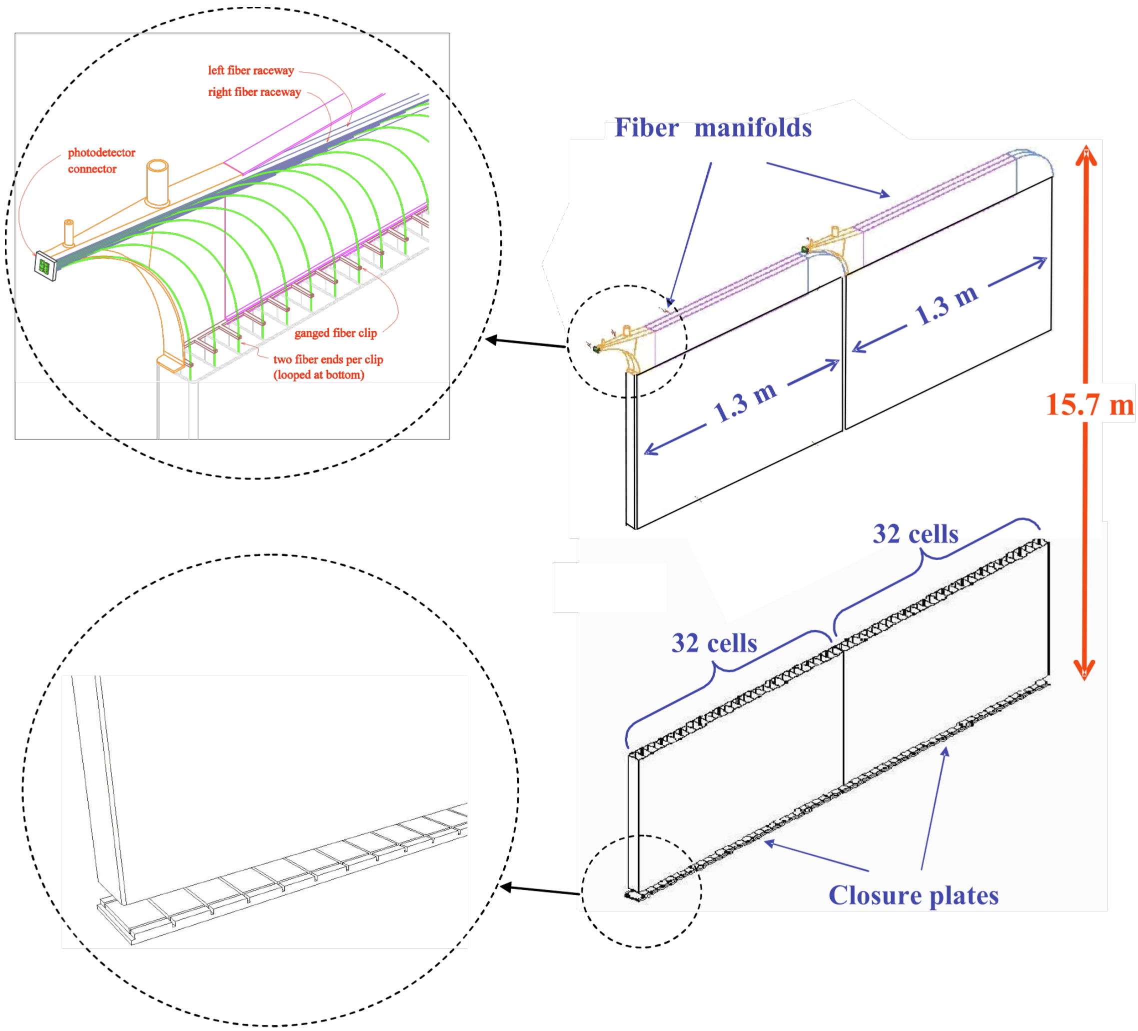
NOνA Detector Design



- 73% of the detector is optically active
- ~4 cm x 6 cm x 15.7 m long PVC cells filled with liquid scintillator (mineral oil + 5% pseudocumene + wavelength shifter)
- A loop of wavelength shifting fiber collects light and brings it to one end of the cell
- The orientation of the cells alternates in every plane; epoxy holds planes together

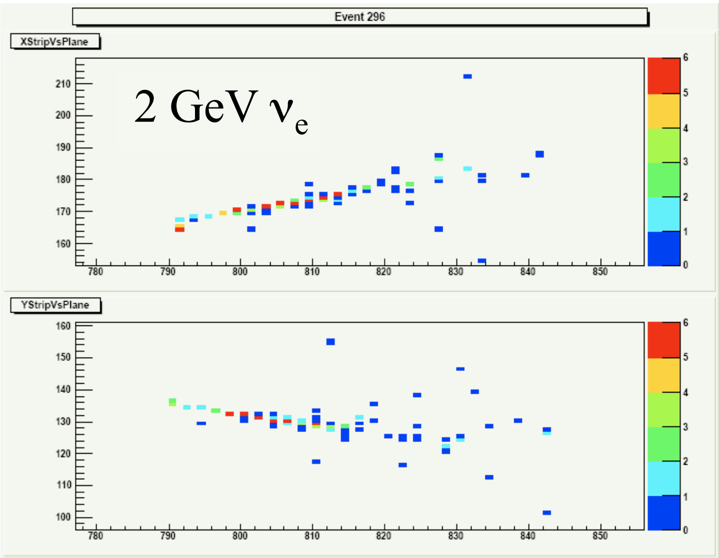
NOνA Extrusions and Readout

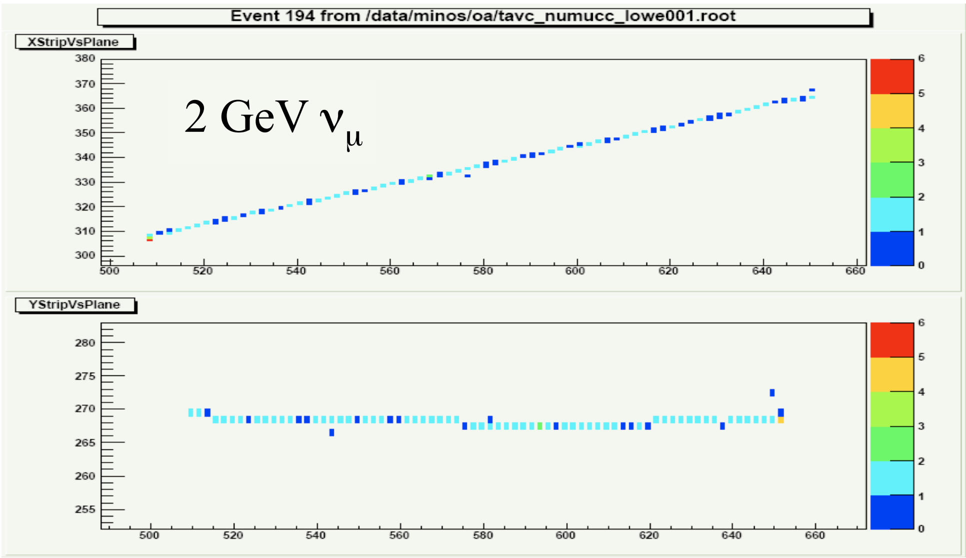
- PVC Extrusions are 32 cells wide, walls are 2-3 mm thick
- Will fit onto a 53 ft semi-trailer
- A closure plate is glued to the bottom, fiber manifold is glued to the top
- Wavelength shifting fibers are collected in fiber manifolds and attached to avalanche photodiodes (APD)
- The two fibers from each cell are connected to one channel of a 32 channel APD
- APDs have an efficiency of 85% at 500 nm and operate at -15 C



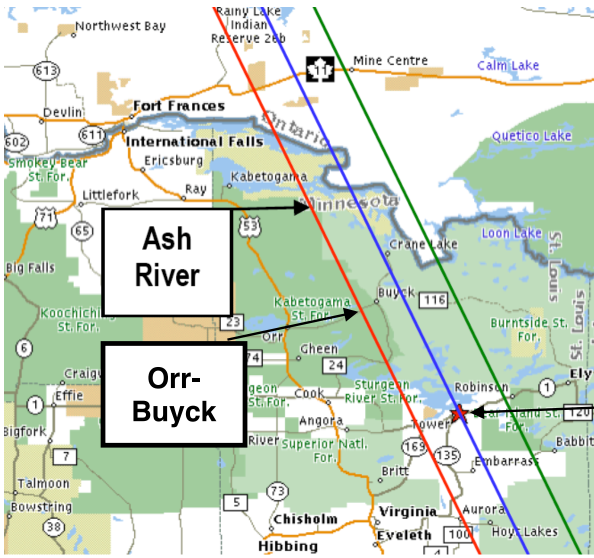
Detector Performance and Sample Events

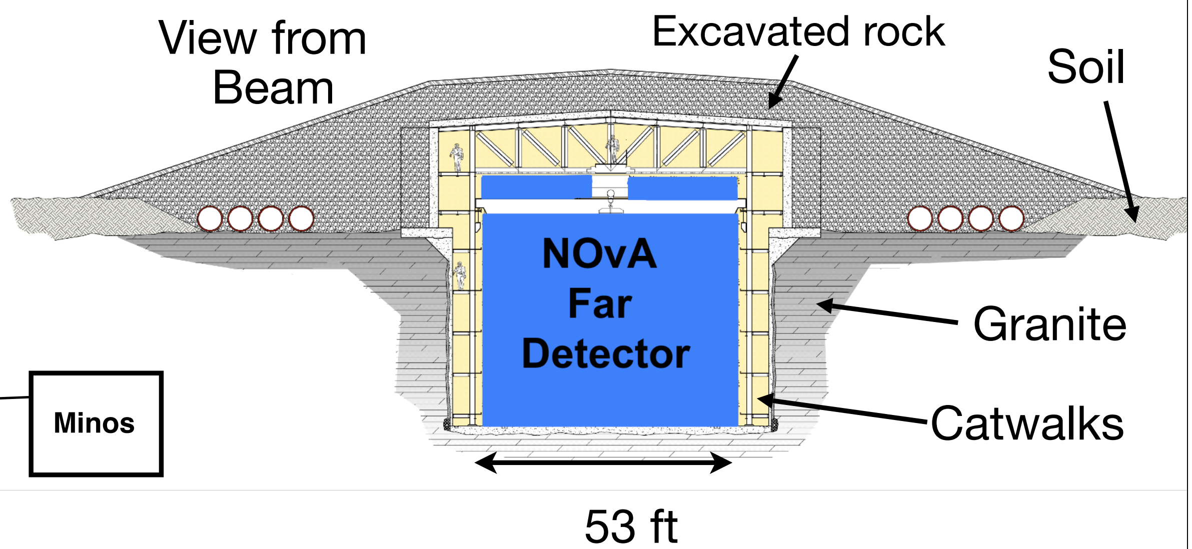
- ~20 photoelectrons per minimum ionizing particle reach the end of each cell
- Expected energy resolution for electrons is 6% at 2 GeV
- Muon quasi-elastic resolution is 3.5% at 2 GeV





Far Detector

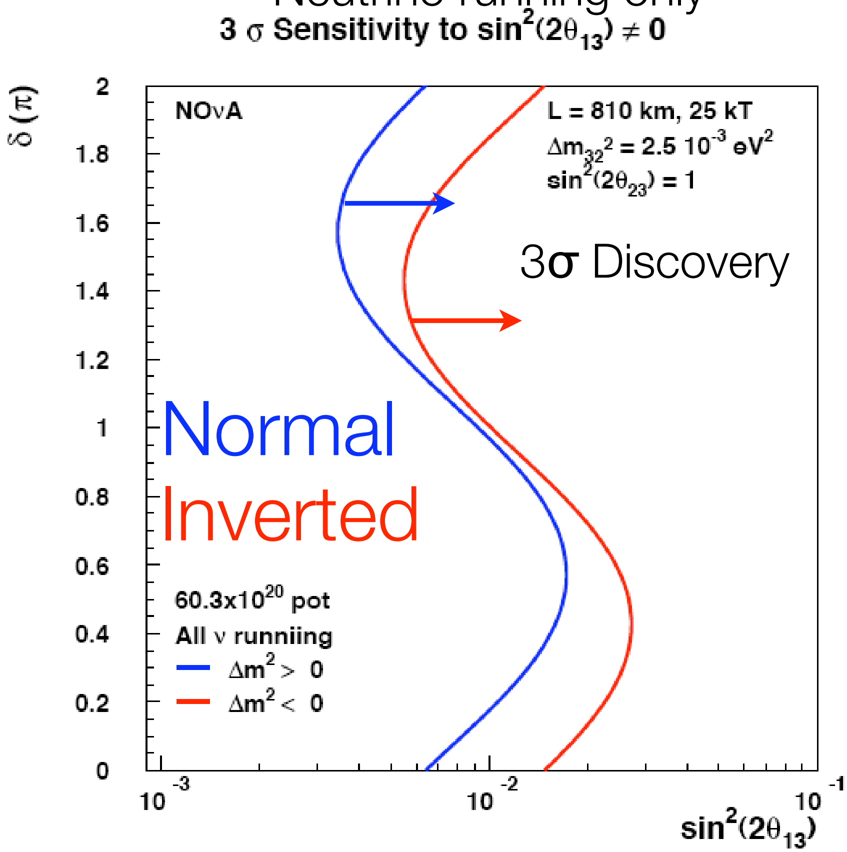




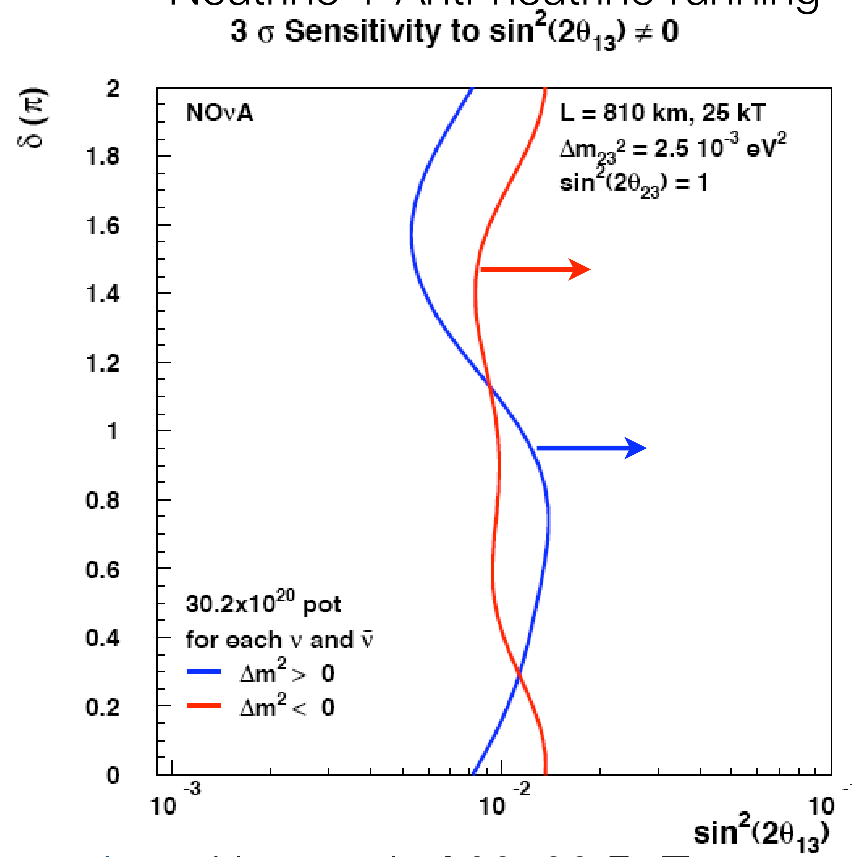
- Two sites under consideration: Ash River is prime candidate, Orr-Buyck Road is the backup
- Detector total mass is 25 kton
- Detector will be sunk into granite for containment and shielding
- Overburden of 3 m of excavated rock (~=2m of solid rock)
- Muons and neutrons are unlikely to look like ν_es, but gammas might
- A shielding of 4m of rock (8 attenuation lengths) reduces photon background to 1 event in 6 yrs. 2 m overburden gives an average slant depth of 4 m.

Sensitivity for 3σ Observation of $\theta_{13} > 0$

Neutrino running only

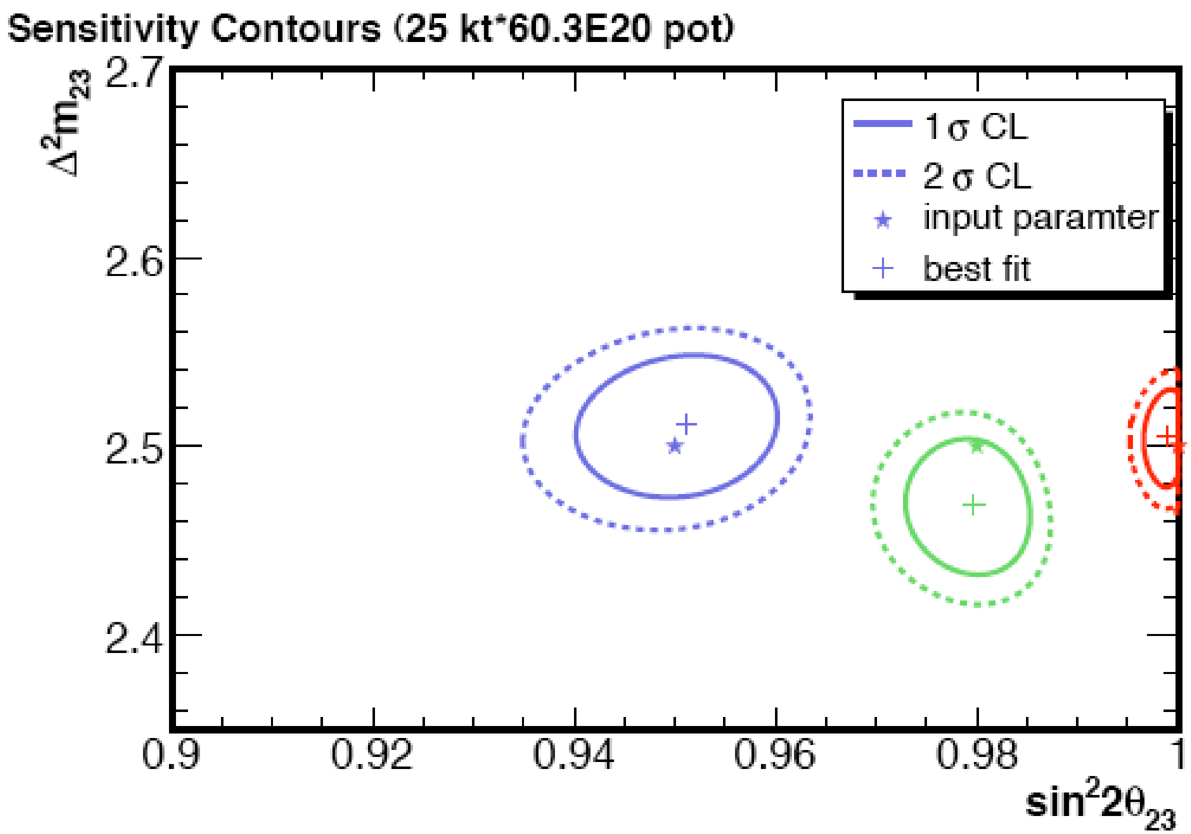


Neutrino + Anti-neutrino running



- 3σ contours shown above, for 6 years of running with a total of 60e20 PoTs
- Sensitivity depends on the order of the mass hierarchy and the value of the CP violating phase, δ

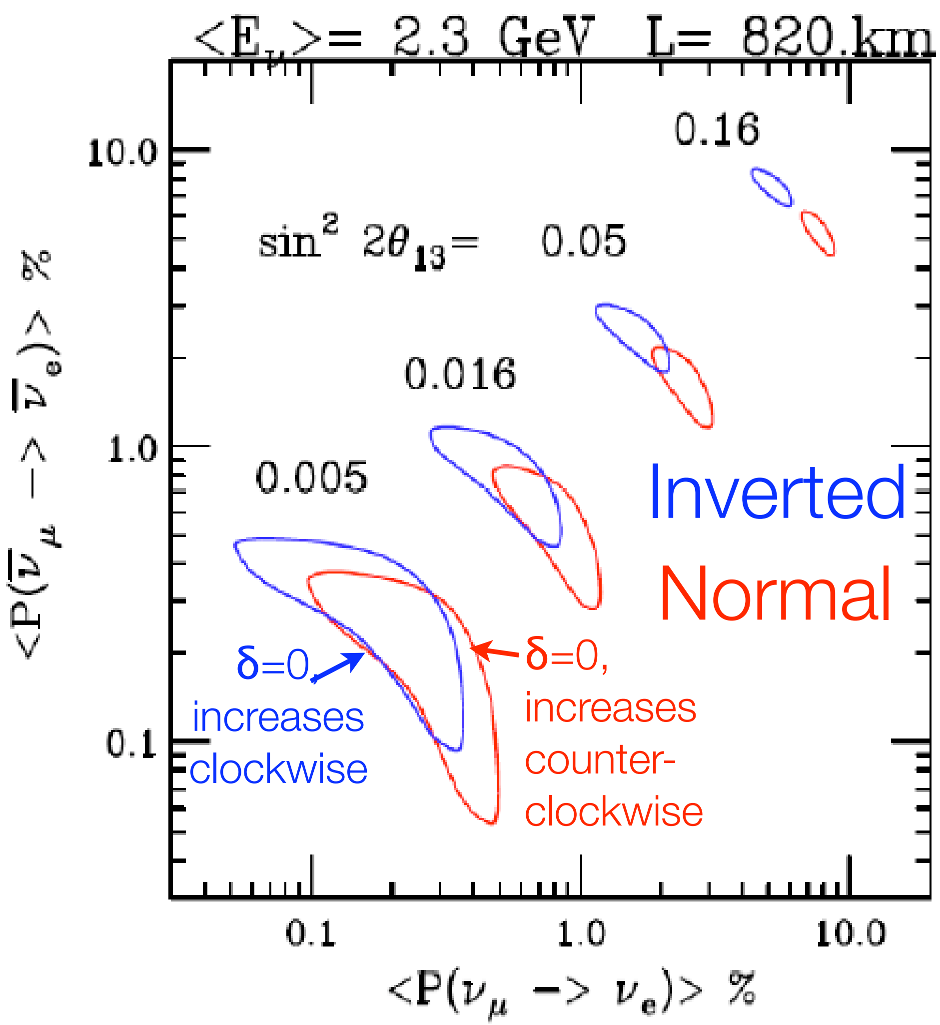
Precision for θ_{23} Measurement



- Allows for a measurement of $\sin^2 2\theta_{23}$ to ~1%

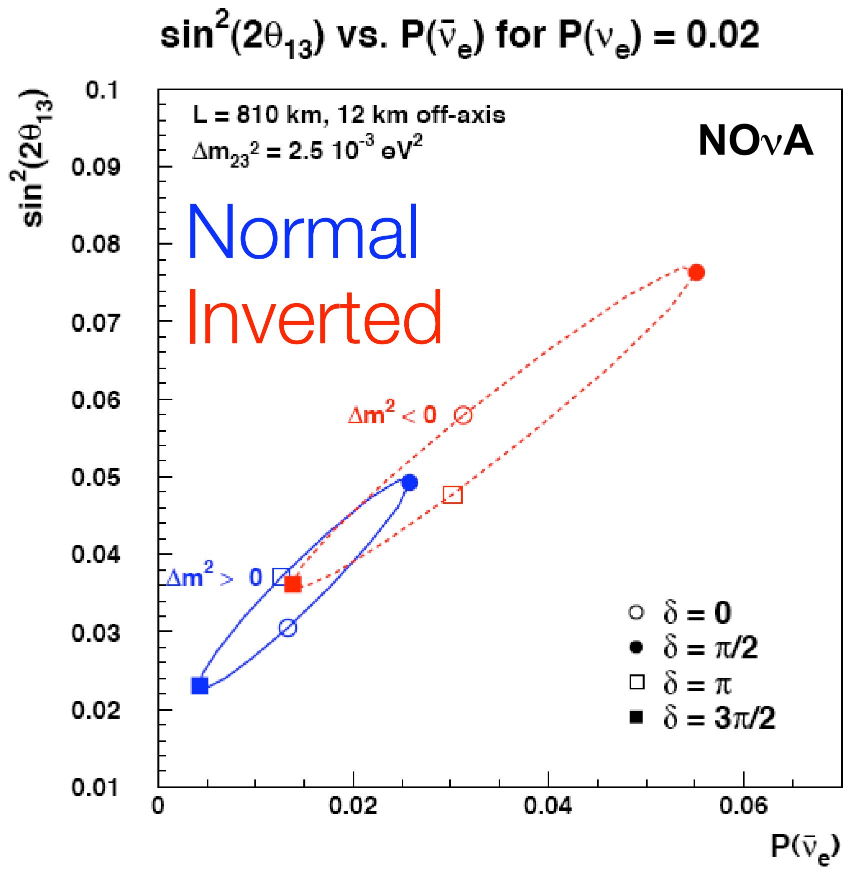
Determining the Mass Hierarchy

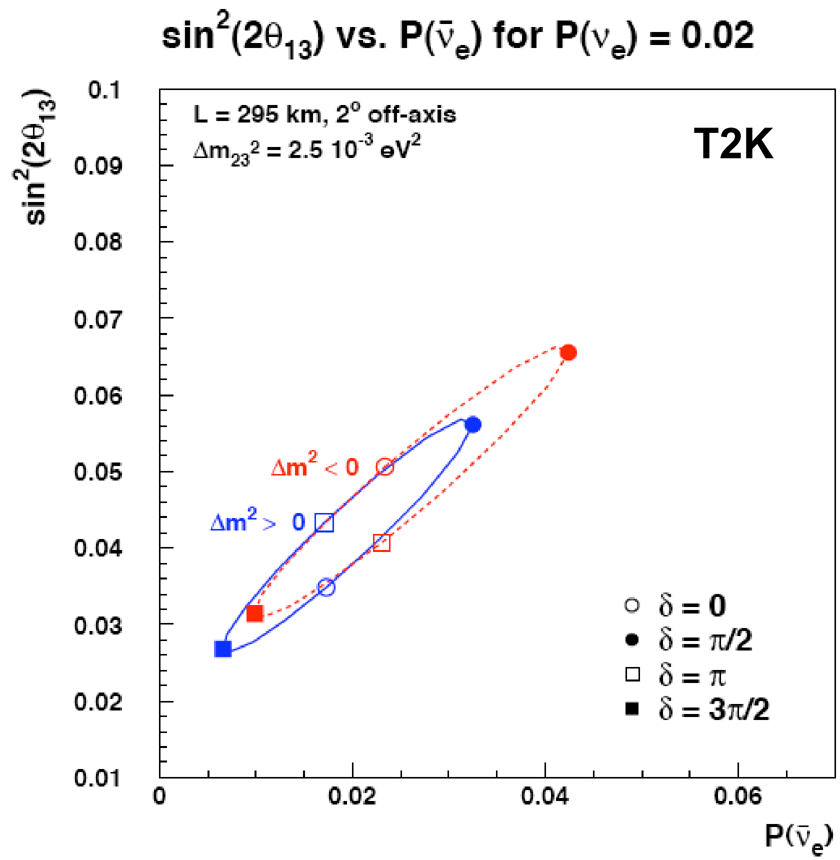
- CP violation causes a difference in the oscillation probability for neutrinos vs anti-neutrinos.
- Matter effects will also do this since matter has electrons, but not anti-electrons. The size of the difference depends on the mass hierarchy.
- Need to know the mass hierarchy to remove the “false” matter-induced CP violation to probe the intrinsic CP violation.
- The larger θ_{13} is the better the separation is, regardless of δ.



Matter Effects in NOνA vs T2K

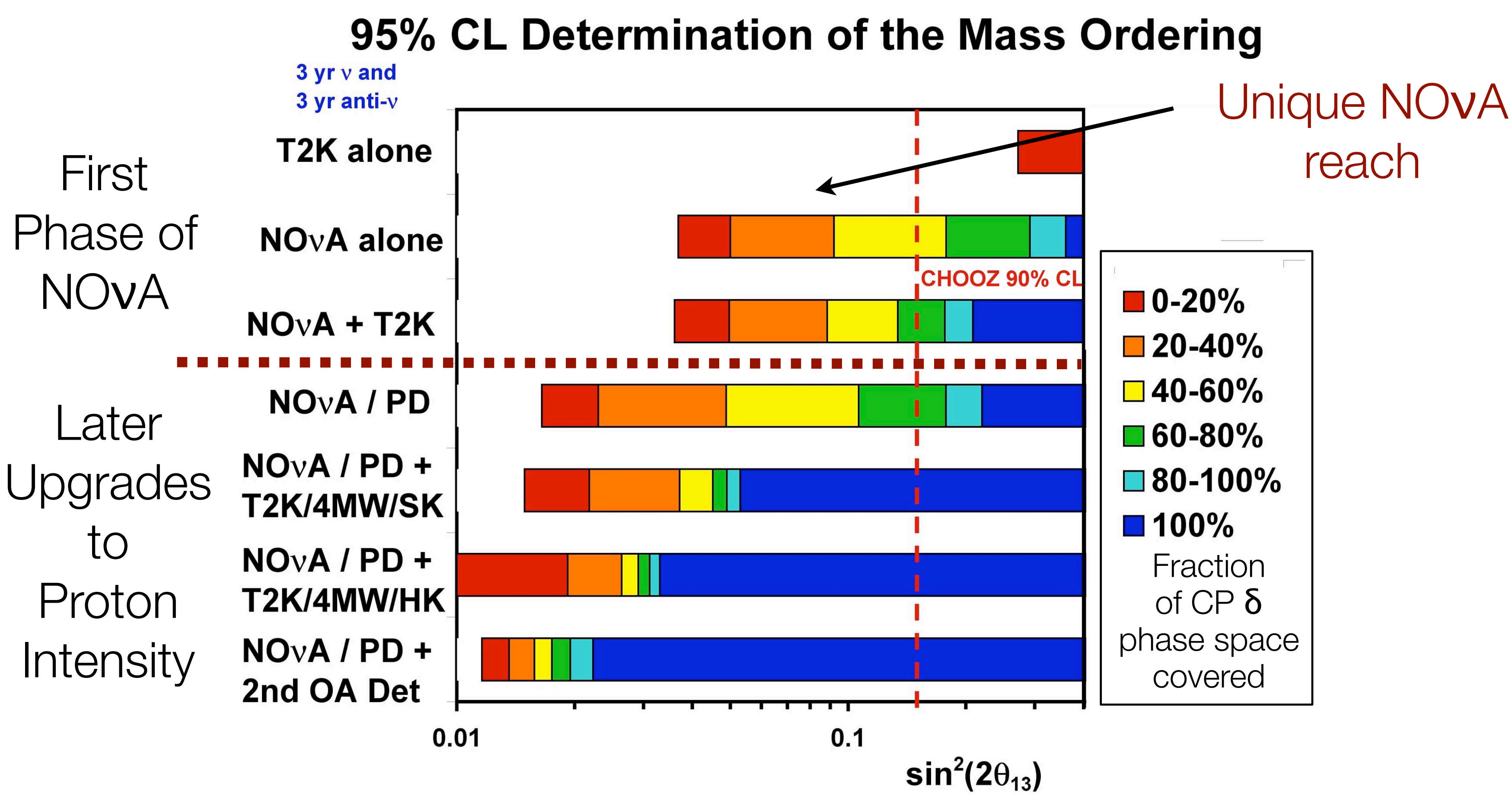
From G. Feldman's talk to P5





- Matter effects are larger in NOνA due to longer baseline
- Both would be greatly helped by an independent measurement of θ_{13}, such as from a reactor neutrino experiment

Sensitivity for Mass Hierarchy



- With a 2 MW proton source for NOνA and a 4 MW source for T2K, it is possible to determine the hierarchy down to $\sin^2 2\theta_{13}$=0.05 for any δ

Summary and NOνA Status

- Detector will be sensitive to ν_e appearance for $\sin^2 2\theta_{13} > 0.01$
- Can make precision measurement of $\sin^2 2\theta_{23}$ to 1%
- NOνA can probe the mass hierarchy and look for CP violation

- Collaboration of ~150 scientists from 28 institutions
- Proposal submitted last spring
- NOνA has received CD 0 approval and was recommended for CD 1 approval in April
- Expect CD 2 review this fall
- Had an external engineering review in January
- Integration prototype detector to be assembled on surface at Fermilab in Spring 2007, will see off-axis NuMI neutrinos (75 mrad)
- If construction begins in 2008, will be completed in 2012 (First 5 kt operational in early 2011)