PROCEEDINGS OF SCIENCE

Status of NOvA: NuMI Off-Axis ν_e Appearance Experiment

Luke A. Corwin for the NOvA Collaboration*
Indiana University
E-mail: corwin@fnal.gov

NOvA is a long-baseline neutrino experiment consisting of the NuMI (Neutrinos at the Main Injector) beam, a prototype Near Detector on the Surface (NDOS), a Near Detector underground at Fermilab adjacent to the MINOS cavern, and a Far Detector in northern Minnesota. The status of the experiment, currently under construction, is presented.

XV Workshop on Neutrino Telescopes,
11-15 March 2013
Venice, Italy

*Speaker.

PoS(Neutel 2013)029

1. Who? (Collaboration)

The NOvA Collaboration consists of 180 collaborators from 34 institutions representing 6 nations. A group photograph is shown in Figure 1.

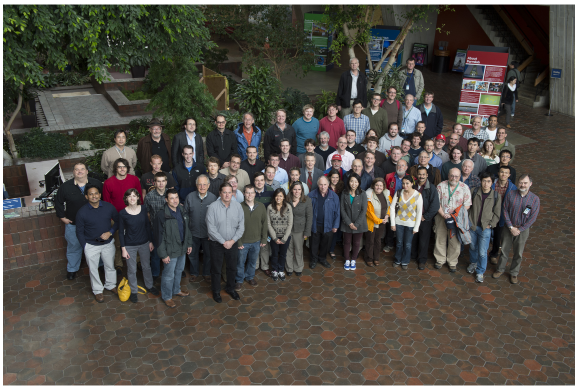

Figure 1: A subset of the NOvA collaboration was photographed at the Oct. 2012 Collaboration Meeting at Fermilab [1].

2. Where? (Geographic Overview)

The NOvA experiment consists of the NuMI (Neutrinos at the Main Injector) beam, a prototype Near Detector on the Surface (NDOS, Figure 4), a Near Detector underground at Fermilab adjacent to the MINOS cavern (Figure 3), and a Far Detector in northern Minnesota (Figure 2). The relative positions of the detectors are shown in Figure 2.

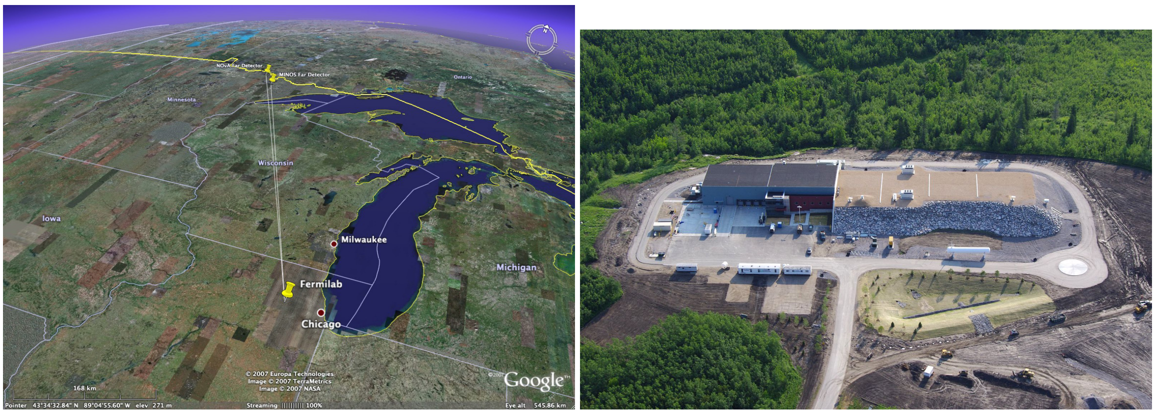

Figure 2: Left: The Near Detector and NDOS are represented by the lowermost pushpin in this map. The Far Detector location is represented by the upper lefthand pushpin [2]. Right: Aerial view of the NOvA Far Detector building [4] .

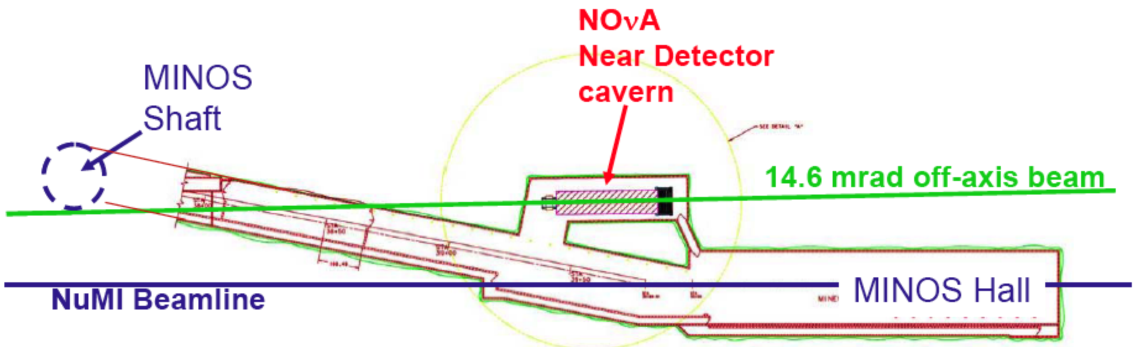

Figure 3: A plan view of the MINOS access tunnel from the vertical MINOS shaft to the MINOS hall. The location of a new NOvA cavern is shown [8].

Figure 4: At left is a photograph of prototype Near Detector on the Surface (NDOS) [11]. At right is a photograph of the nearly completed Near Detector Cavern [12]. Installation of the Near Detector is currently underway.

3. Why? (Physics Goals)

The generic probability of producing a neutrino in one weak eigenstate α and detecting it after some travel time t in a weak eigenstate β is given by

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\alpha j} e^{-\frac{im_j^2 t}{2E}} U^*_{j\beta} \right|^2 , \tag{3.1}$$

where U is the PMNS matrix. This is shown graphically in Figure 5.

The following physics goals of the NOvA experiment are discussed in these proceedings

1. Improve the precision of our knowledge of θ_{13}.
2. Determine whether θ_{23} is maximal (i.e. if $\sin^2(2\theta_{23}) = 1$). If $\sin^2(2\theta_{23}) \neq 1$, determine if $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ$.

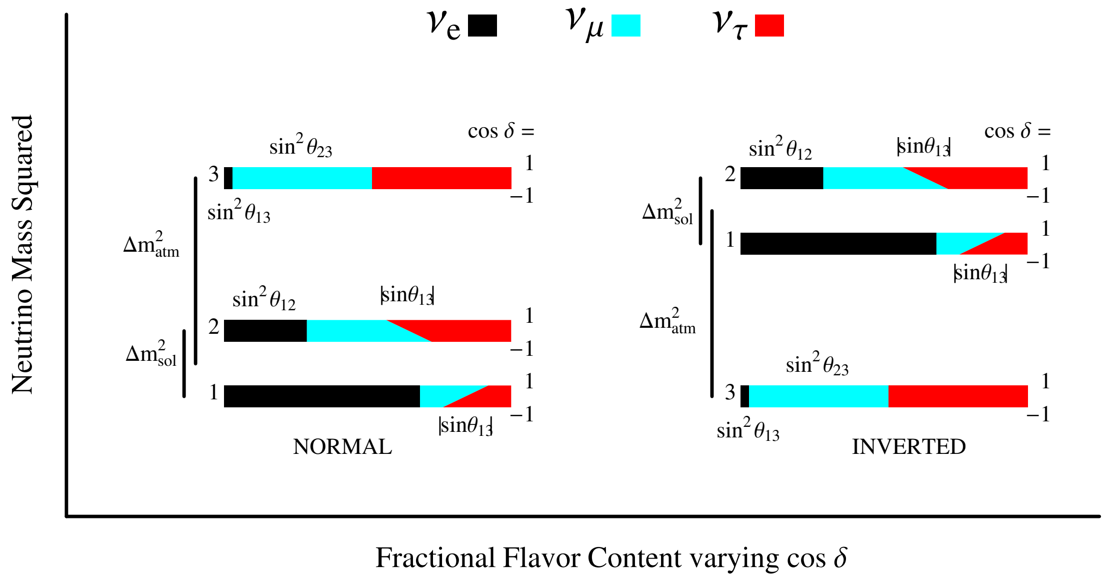

Figure 5: The neutrino mass eigenstates ν_1, ν_2, and ν_3 are each admixtures of the weak eigenstates ν_e, ν_μ, and ν_τ; the relative proportions of the mass eigenstates in the weak eigenstates are determined by the values of the weak mixing angles and the unmeasured CP phase δ. In general $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$. The sign of Δm^2_{atm}, which is equivalent to Δm^2_{32}, is unknown [5].

3. Attempt to measure or place limits on δ_{CP}.

4. Search for the neutrino mass hierarchy. Determine if the hierarchy is "normal" ($m_3 > m_1$) or "inverted" ($m_3 < m_1$). This is equivalent to measuring the sign of Δm^2_{32}.

5. Detect neutrinos from a galactic core-collapse supernova should one occur during the running of the experiment.

4. How? (Methods and Sensitivities)

4.1 Oscillation Physics

The theoretical connections between the oscillation probabilities NOvA will measure and the underlying physical parameters are summarized in Refs. [6, 7].

$$P(\nu_\mu \to \nu_e) = \left| \sum_j U_{\mu j} e^{-\frac{i m_j^2 t}{2E}} U^*_{je} \right|^2 \approx P_{\text{atm}} + 2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}}\cos(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta) \quad (4.1)$$

In the $\mp$ term, the minus sign refers to neutrinos, and the plus sign to antineutrinos.

$$P_{\text{atm}} = \sin^2(\theta_{23})\sin^2(\theta_{13})\sin^2(\Delta_{31}) \quad (4.2)$$

and

$$P_{\text{sol}} = \cos^2(\theta_{23})\cos^2(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}), \quad (4.3)$$

where $\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$.

Neutrinos travelling through matter experience a modification of oscillation probabilities given by

$$P_{\text{matter}}(\nu_\mu \to \nu_e) \approx \left(1 + \frac{E\Delta m^2_{32}}{2\sqrt{2}G_F N_e}\right) P_{\text{vacuum}}(\nu_\mu \to \nu_e). \tag{4.4}$$

Note that Equation 4.4 depends on the value of Δm^2_{32} not on its absolute value. Therefore, the long baseline of the NOvA experiment provides enhanced sensitivity to the mass hierarchy. Also, note that the oscillation probabilities are functions all of the parameters in physics goals 1 - 4 from § 3.

4.2 Measurements

Common NOvA event topologies are shown in Figure 6.

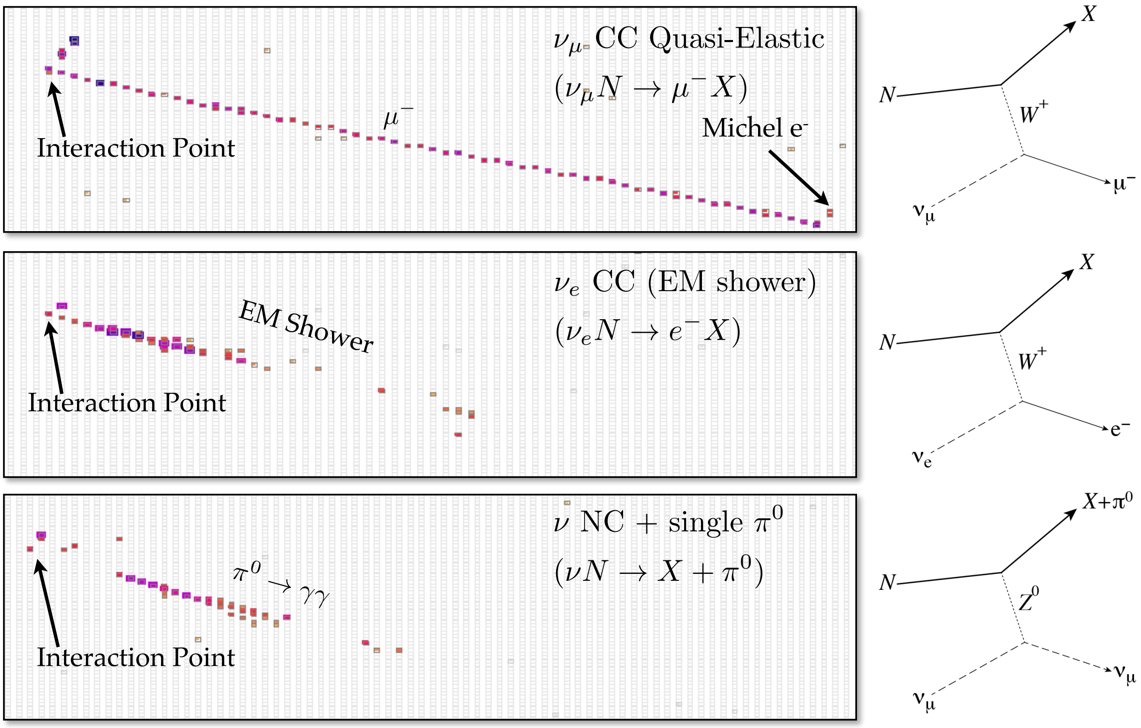

Figure 6: Common simulated NOvA event topologies. Adapted from Ref. [3]

We will take data with neutrino-dominated and antineutrino-enhanced beams. As Figures 7 and 8 show, measuring in both modes is necessary in much of the allowed phase space. We will detect ν_μ and ν_e charged current interactions with the near and far detectors. In our first analyses we will measure $P(\nu_\mu \to \nu_\mu)$, $P(\nu_\mu \to \nu_e)$ and their charge conjugates. In later analyses, with higher statistics available, we will also measure and analyze the neutrino energy spectra at the Far Detector.

4.3 Sensitivities

Figures 7 and 8 show "bi-probability" plots, where the probability of $\overline{\nu}_e$ appearance at the far detector $P(\overline{\nu}_e)$ is plotted against $P(\nu_e)$. The values of those two probabilities are determined

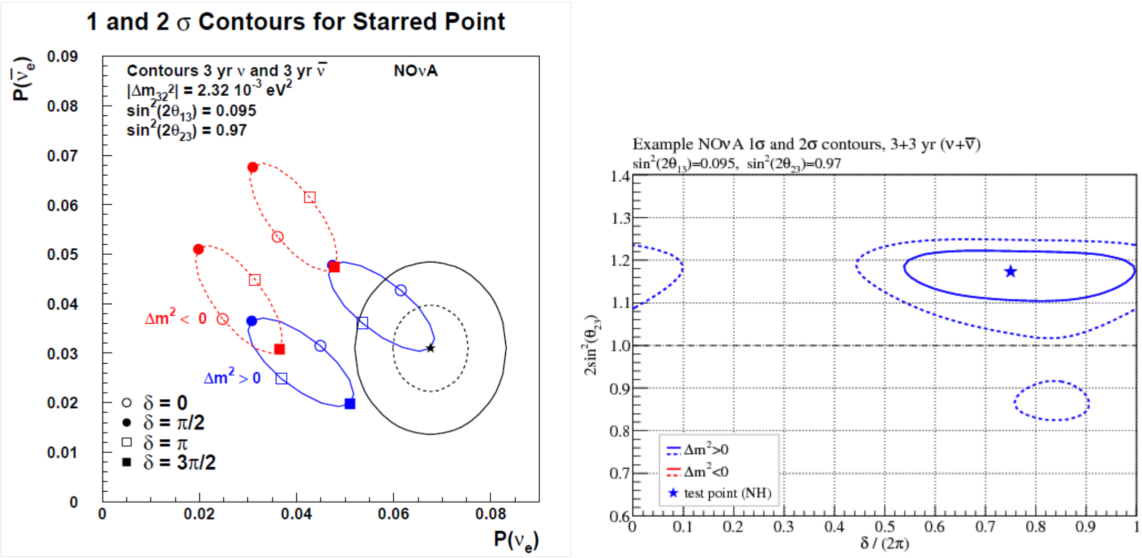

Figure 7: At this best-case point, we exclude the wrong hierarchy and a good fraction of δ_{CP} at 2 standard deviations [8].

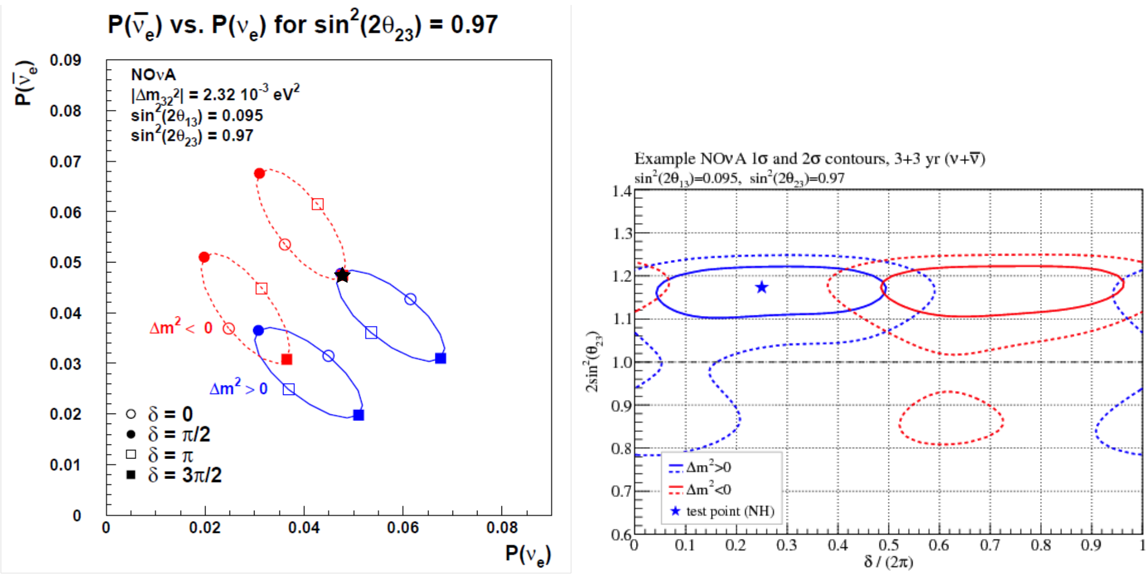

Figure 8: At this point, we cannot determine the hierarchy, but we can make conditional statements about it and δ_{CP}. In both cases, we select $\theta_{23} > 45^\circ$ at 1 standard deviation [8].

by δ_{CP}, θ_{23}, and the mass hierarchy. For some points in this phase space (e.g. Figure 7), we can determine all three parameters without the need for the antineutrino-enhanced beam. However, to ensure maximum sensitivity for less fortuitous points in phase space (e.g. Figure 8), we plan to carry out measurements in both beams.

We find that the best sensitivity for determining whether θ_{23} is maximal occurs when NOvA data are combined with complementary data from reactor experiments, as shown in Figure 9 .With complimentary data from T2K, NOvA could be able to determine the hierarchy at 1 σ for almost

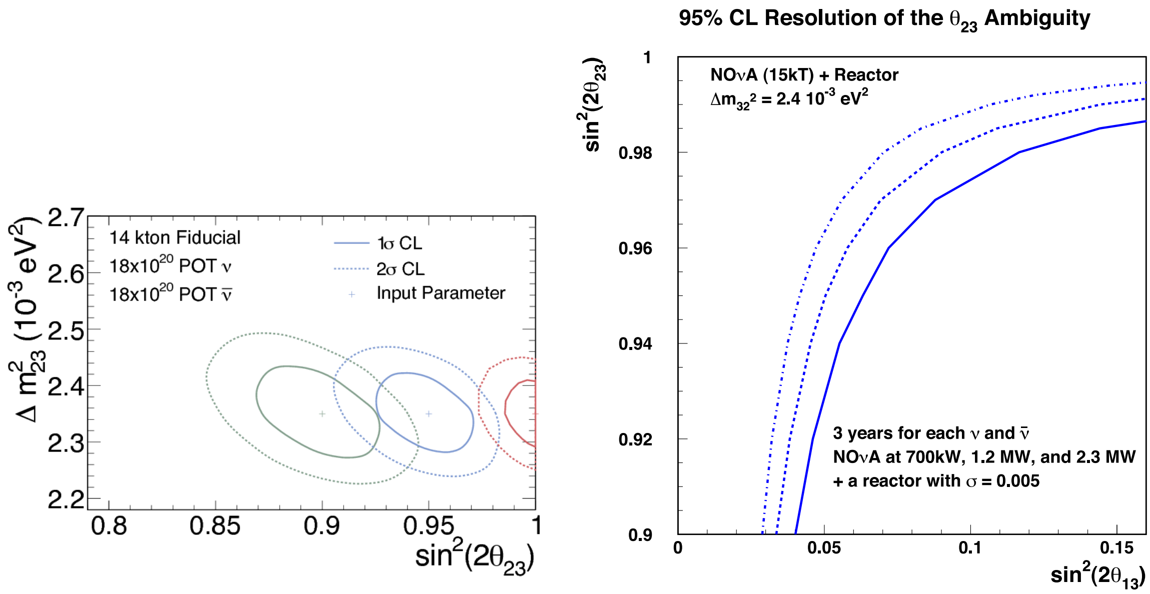

Figure 9: NOvA has good sensitivity to whether θ_{23} is maximal. Combining NOvA data with precision reactor data could determine the octant for a large range of values [8]. In the region below and to the right of the curves in the right-hand figure, the octant is resolved.

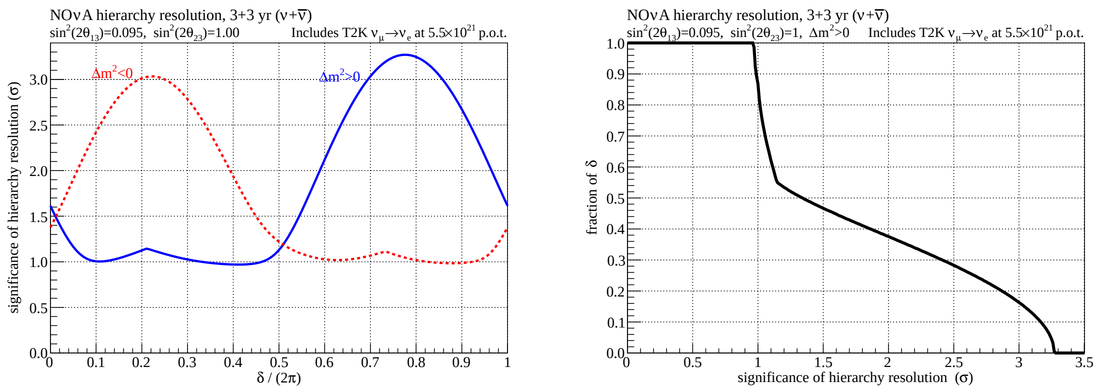

Figure 10: With complimentary data from T2K, NOvA could be able to determine the hierarchy at 1 σ for almost all values of $\delta_{\rm CP}$ [3].

all values of $\delta_{\rm CP}$, as shown in Figure 10.

For a supernova at the center of the Milky Way galaxy, the NOvA Far Detector is expected to see 5000 neutrinos with a time distribution shown in Figure 11.

5. What? (Detector Description)

The NOvA near and far detectors are being constructed approximately 14 mrad off the central axis of the NuMI beam. At this angle, as shown in Figure 12, the energy distribution of the neutrinos is narrowly distributed around the energy at which the $\nu_\mu \to \nu_e$ oscillation is maximal.

The NOvA detectors are constructed from PVC cells filled with liquid scintillator and grouped into alternating planes. As shown in Figure 13, a wavelength-shifting optic fiber is strung through

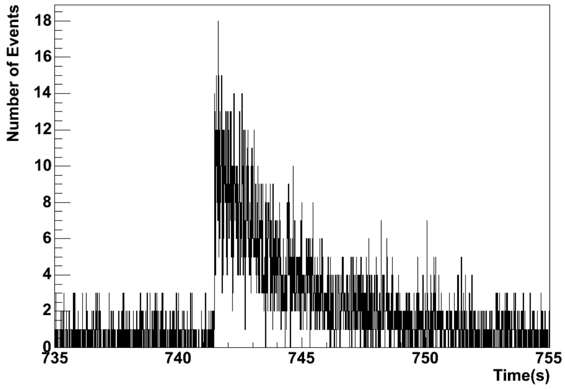

Figure 11: A simulation of $\sim$ 15 min. of data with $\sim$ 10 s supernova signal. The distribution has 10 ms time bins with 3 m overburden. Under these conditions, the NOvA Far Detector would see a burst of 5000 neutrinos from a supernova at the center of the galaxy [9].

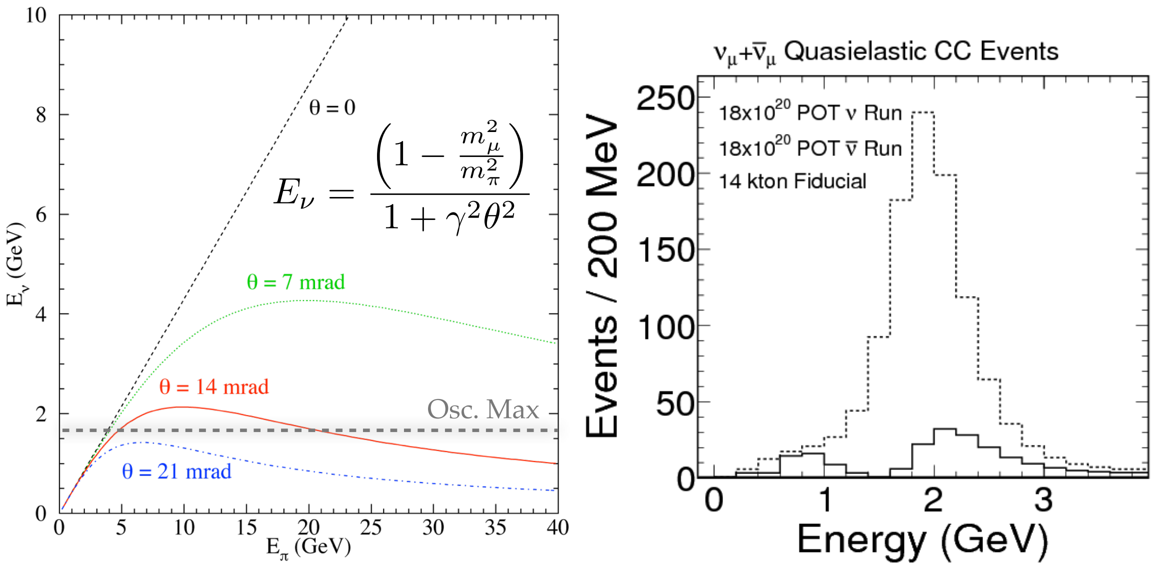

Figure 12: At left, the calculated energy spectra of neutrinos at several off-axis angles is plotted against the energy distribution of their parent π. At right, simulated oscillated and un-oscillated energy spectra for ν_μ and $\overline{\nu}_{mu}$ quasielastic charged current events are shown [8].

each cell to carry light from the interaction point to the APDs that convert scintillation photons into electronic signals.

The Far Detector will have a total mass of 14000 tons with rectangular dimentions $63 \times 15.7 \times 15.7$ m. It will consist of 28 blocks (numbered 0 through 27), each consisting of 32 planes of cells. The Near Detector will have a total mass of 330 tons with rectangular dimentions $14.3 \times 3.9 \times 3.9$ m.

The NDOS has been operational since Oct. 2010 and has collected NuMI data in the MINOS beam. It has taught us much about detector assembly. Though it is not fully instrumented and has been instrumented in multiple different configurations, it has been remarkably productive and useful (e.g. Figure 14).

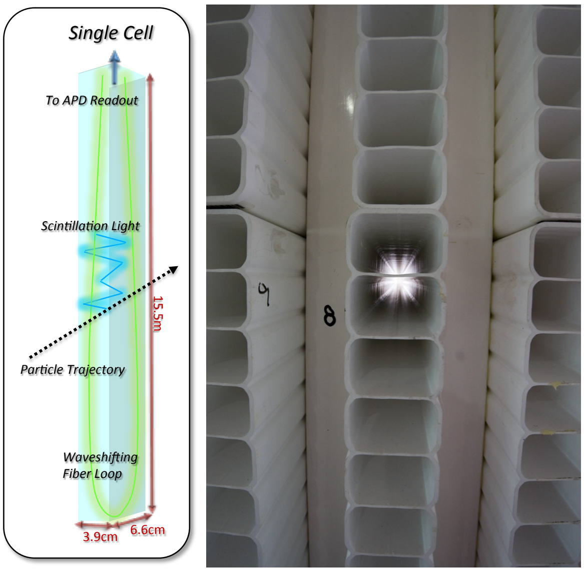

Figure 13: The NOvA detectors are constructed from PVC Cells filled with liquid scintillator and grouped into alternating planes [10].

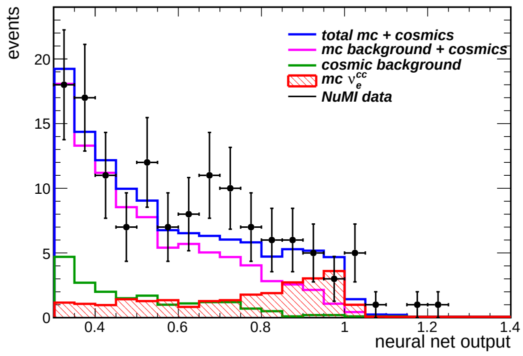

Figure 14: ν_e in NDOS: Even with sparse instrumentation, we have identified electron neutrino events in the data excess above background. This is promising for the fully instrumented detectors [8].

6. When? (Status, schedule and outlook)

As of Mar. 11, 2013, Far Detector Block 9 was being assembled, and it was 31% complete. Blocks 0 through 8 were installed, representing $\approx 33\%$ of the final detector volume. Blocks 0 through 2 were filled with scintillator; 13% of Block 0 and 4% of Block 1 were fully instrumented.

In the fully instrumented cells, we have detected the first scintillator light from the Far detector, which was generated by cosmic rays. Many commissioning tasks remain ahead, but progress so far is encouraging.

As shown in Figure 15, the detectors are scheduled to be complete by Nov. 2014. We expect to have a partial Far Detector (3 kt) reading out beam data in June 2013, and the Near Detector

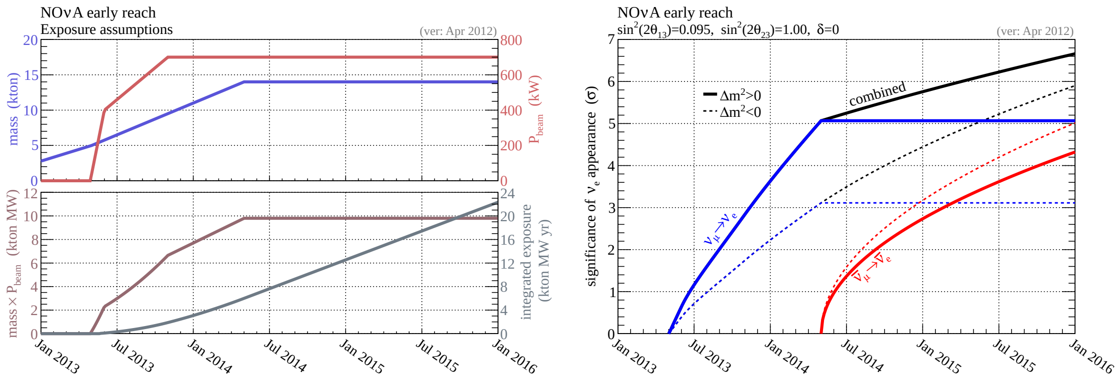

Figure 15: Estimated exposure and physics reach of the NOvA experiment as of April 2012 [3].

complete in Feb. 2014. The first analyses already well underway, and we plan to have the first two-detector analyses for Neutrino 2014.

References

[1] R. Hahn, *NOvA Collaboration photo*, Fermilab Visual Media Services Image 12-0287-01.

[2] `http://www-nova.fnal.gov/images_v2/graphics/NOVA-Looking-North-large.jpg`

[3] NOvA Collaboration, *NOvA Blessed Plots and Figures Gallery*, `http://nusoft.fnal.gov/nova/blessedplots/gallery.html`

[4] C. Herman, *Neutrino science meets Minnesota wilderness*, *Symmetry Magazine* **8** (2011) 26.

[5] O. Mena and S. Parke, *Unified Graphical Summary of Neutrino Mixing Parameters*, hep-ph/0312131.

[6] V. Barger, *et al.*, *Matter Effects on Three-Neutrino Oscillations* , *Phys. Rev. D* **22** (1980) 2718.

[7] H. Nunokaka, S. Parke, and J. Valle, *CP Violation and Neutrino Oscillations*, *Prog. Part. Nucl. Phys.* **60** (2008) 338 [arXiv:0710.0554].

[8] NOvA Collaboration, *NOvA Official Plots and Figures*, `http://www-nova.fnal.gov/plots_and_figures/plot_and_figures.html`

[9] M. Messier, *The NOvA Experiment*, Presented at *Implications of Neutrino Flavor Oscillations (INFO) 2011*, Santa Fe, NM, USA, 18 July 2011.

[10] R. Hahn, *NOvA Collaboration photo*, Fermilab Visual Media Services Image 10-0127-02.

[11] R. Hahn, *NOvA Prototype Near Detector on surface*, Fermilab Visual Media Services Image 11-0124-13.

[12] C. Arnold, *Civil construction progress of the NOvA Near Detector Hall*, Fermilab Visual Media Services Image 13-0059-19.