EPJ Web of Conferences **70**, 00076 (2014)
DOI: 10.1051/epjconf/20147000076

NOvA experiment in light of large θ_{13}.

Denis Perevalov.

[1] *Fermi National Accelerator Laboratory, Batavia IL, USA*

Abstract. NOvA is an off-axis long baseline neutrino experiment searching for $\nu_\mu \to \nu_e$ oscillations using an upgraded NuMI neutrino beam from Fermilab, Batavia, IL. The main physics goal is a measurement of the CP violation and establishing the neutrino masses hierarchy. A large 14 kton Far detector, comprised of liquid scintillator contained in extruded PVC cells, will also provide an opportunity for other non-accelerator physics searches. While civil construction at the far detector is underway, a smaller prototype near detector has been assembled at Fermilab and is being studied.

1 Introduction

NOvA stands for NuMI Off-Axis ν_e-Appearance Experiment. The NuMI (Neutrinos from the Main Injector) facility [1] provides a neutrino source, which mostly consists of ν_μ and $\bar{\nu}_\mu$ type of neutrinos. These neutrinos travel through the earth to the Far Detector which is 810 km away from the neutrino source. The detector is paced 14 mrad off-beam axis, which privides a narrow neutrino flux around 2 GeV, optimized for the $\nu_\mu \to \nu_e$ first oscillation maximum. The ability to operate in two modes, where either ν_μ or $\bar{\nu}_\mu$ neutrino species content is enriched allows to measure probabilities of oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. Recent findings of a relatively large value of the θ_{13} parameter of the neutrino mixing matrix from Double Chooz, Daya Bay, Reno and T2K makes the NOvA experiment very interesting in terms of determining or placing limits on currently unknown neutrino properties, such as neutrino mass hierarchy, is there a CP-violation in the lepton sector.

2 Non-zero Value of θ_{13}

At the end of 2011 through beginning of 2012 four experiments: T2K, Double Chooz, Daya Bay and Reno have reported a meuurement of the θ_{13} parameter of the neutrino mixing matrix. The measurements of θ_{13} from these experiments are shown in Fig.1. They all appear to be consistent with each other and together claim at least $5-\sigma$ confidence of excluding the hypothesis of $\theta_{13} = 0$. A combined average of the experiments leads to

$$sin^2 2\theta_{13} = 0.092 \pm 0.012.$$

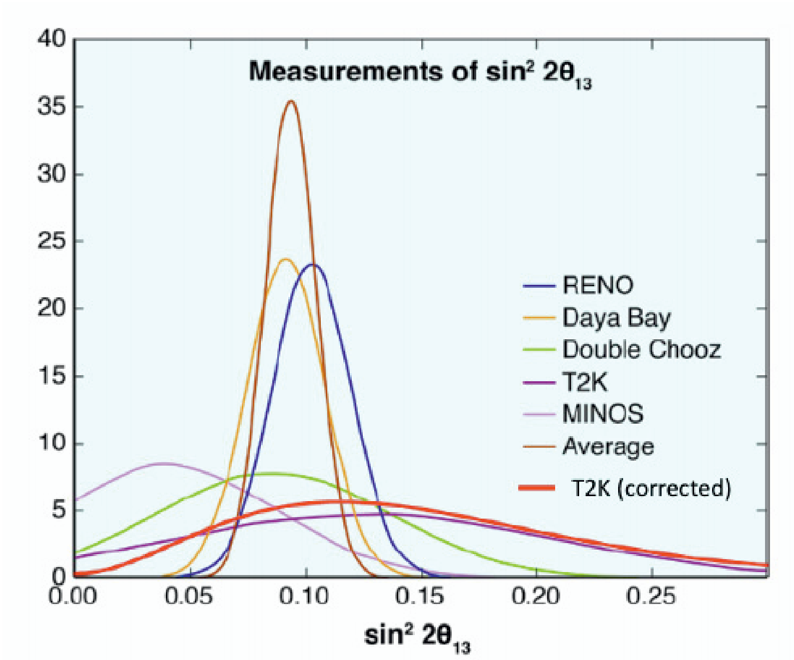


Figure 1. Combined measurements of θ_{13} from several experiments.

3 Physics of NOvA.

3.1 Sensitivity to δ_{CP} and Mass Hierarchy.

As mentioned above NOvA will be measuring probabilities of oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$.

One can calculate these probabilities in a general form, assuming three neutrino case:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &\approx sin^2 2\theta_{13} sin^2\theta_{23} \frac{sin^2(A-1)\Delta}{(A-1)^2} \\
&+ 2\alpha sin\theta_{13} sin\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sin(A)\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} sin\Delta \\
&+ 2\alpha sin\theta_{13} cos\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sin(A)\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} cos\Delta, \\
P(\bar{\nu}_\mu \to \bar{\nu}_e) &\approx sin^2 2\theta_{13} sin^2\theta_{23} \frac{sin^2(A-1)\Delta}{(A-1)^2} \\
&- 2\alpha sin\theta_{13} sin\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sin(A)\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} sin\Delta \\
&+ 2\alpha sin\theta_{13} cos\delta_{CP} sin2\theta_{12} sin2\theta_{23} \frac{sin(A)\Delta}{A} \frac{sin(A-1)\Delta}{(A-1)} cos\Delta,
\end{aligned} \tag{1}
$$

where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2 L/(4E_\nu)$, $A = \mp G_f n_e L/(\sqrt{2}\Delta)$(minus sign for ν and plus for $\bar{\nu}$ mode, respectively), L is the experiment baseline, E_ν is the neutrino energy.

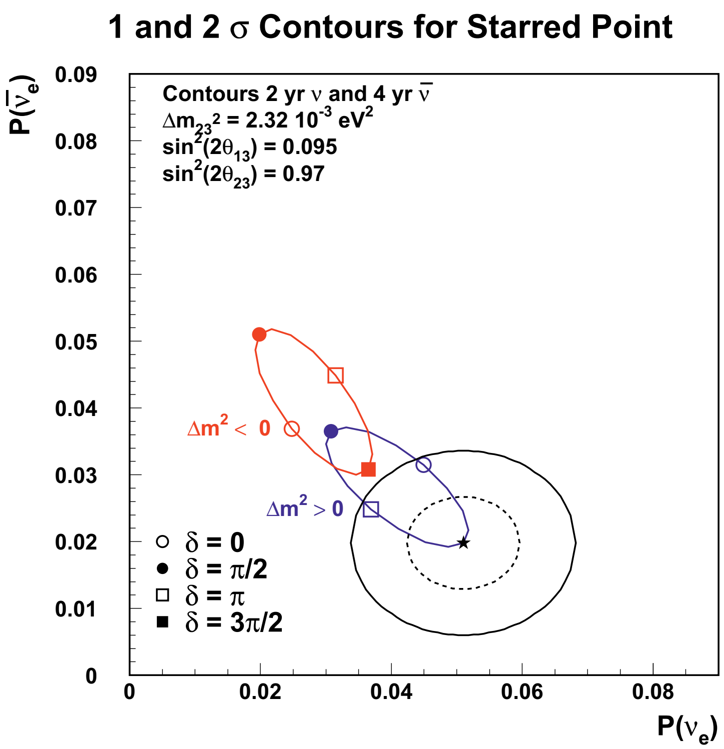


Figure 2. An example of a NOvA measurement.

One can see that the probabilities depend on several parameters, of which currently some are well-known (θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$)), some are less known ($sin2\theta_{23}$) and some are unknown: the sign of Δm^2_{31} - the mass hierarchy and δ_{CP} - CP violating parameter.

By measuring oscillations in both ν and $\bar{\nu}$ modes NOvA will be sensitive for measuring or placing limits on the mass hierarchy, δ_{CP} and the sign of $sin2\theta_{23}$.

In Fig.2 a black star represents an example of a NOvA measurement with black dotted and solid $1-\sigma$ and $2-\sigma$ contours, respectively. One can calculate the probability of oscillations from Eq.(1) for all possibilities of mass hierarchy and δ_{CP} and other parameters fixed, which would result to solutions represented in blue and red lines. Once can see that NOvA is sensitive to determining mass hierarchy and δ_{CP}.

3.2 Beam Off-axis.

NOvA Far and near detectors will be located 14 mrad off the neutrino beam axis. Even though the resulting neutrino flux integral at the NOvA detector location is much smaller than that on axis. But the flux spectrum is much narrower, providing close to monochromatic neutrino energy spectrum around 2 GeV.

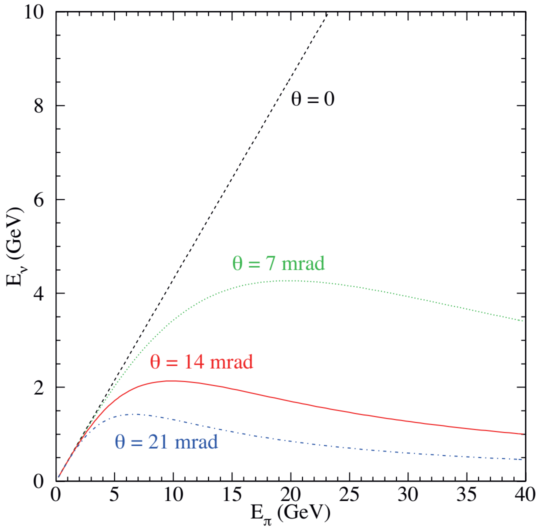


Figure 3. $E_{\nu} asafunctionofpionkineticenergyfordifferentneutrinoanglesrelativetothebeamaxis..$

Using a 2-body $\pi^{+} \rightarrow \mu^{-} + \nu_{\mu}$ decay kinematics, one can obtain the relation between neutrino energy E_{ν} and the pion kinetic energy E_{π} assuming small values of the neutrino angle θ:

$$E_{\nu} \approx \frac{\left(1 - \frac{m_{\mu}^{2}}{m_{\pi}^{2}}\right) E_{\pi}}{1 + \gamma^{2}\theta^{2}.}$$

One can plot the $E_{\nu}(E_{\pi})$ dependence for different values of θ, as shown in Fig.3. As one can see, at on-axis, E_{ν} has a linear dependence on E_{π}. But for off-axis, it becomes fairly independent of the pion energy. Thus, the resulting neutrino flux is narrow, even in a case of a broad pion beam, as shown in Fig.4.

4 The NOvA Experiment.

4.1 Experiment Design.

NOvA will have a complementary pair of detectors constructed 14 mrad off-axis to the NuMI source. Both detectors will be highly segmented tracking calorimeters built from PVC cells. The cells are filled with mineral oil based liquid scintillator for the total of 65% of the active volume [2]. The far detector will be a surface-based 14 kTon volume located 810 km from NuMI in Ash River, Minnesota. A smaller 222 Ton detector will be built about 1 km from the target at the Fermilab site in a 105 meters deep underground cavern.

To accommodate the needs of the experiment, the NuMI beam power will be upgraded to 700 kW during the accelerator shutdown from March to December 2012.

The NOvA detector is built up from extruded PVC cells loaded with TiO_2 [2]. Each cell is 3.8 cm by 5.9 cm in cross section with 90% reflectivity for light at 430 nm. Extrusions are joined to together to produce a sealed module of 32 cells. In the near detector, the modules are either 4.2 m long while

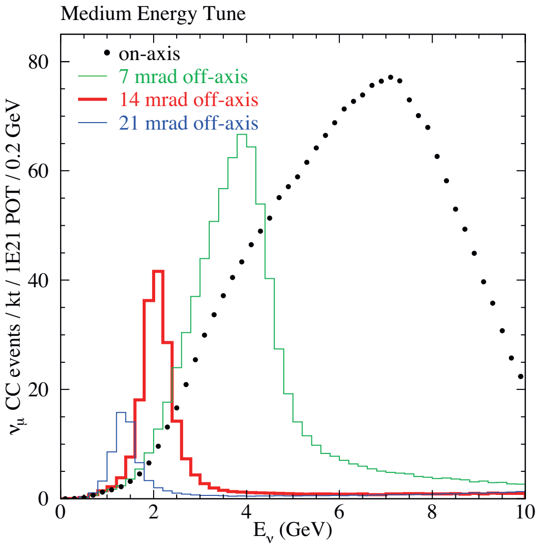


Figure 4. Neutrino flux energy spectra for different values of θ.

far detector modules are 15.6 m long. These modules are glued together into alternating planes of horizontal or vertical orientation to create a self-supporting 32 layer blocks. ~360,000 cells makeup the 14 kTon far detector. In addition, the near detector will have 1.7 m width muon ranger.

PVC blocks are filled in place with mineral oil containing 5% pseudocumene and wavelength shifters to produce 400-450 nm light. The liquid scintillator makes up 65% of the total detector mass [2]. NDOS required ~30,000 gallons of scintillator while the 14 kTon far detector will use over 3 million gallons.

Internal to each cell is a 0.7 mm diameter looped fiber. The fiber shifts the light collected in the scintillator to 490-550 nm [2]. Its ends are routed through the manifold covered to an optical connector where they are available for single sided readout. ~113 km of fiber is used in the near detector design with 13,000 km needed for the far detector.

The light from the fiber ends is incident on Hamamatsu avalanche photodiodes (APD) which have 85% quantum efficiency for 520-550 nm light [2]. The devices are operated at -15 °C with a gain of 100. For NOvA a 20 photoelectron (pe) signal from a minimum ionizing particle at the far end of a far detector sized module is required with a 10-15 pe threshold applied. Based on initial system verification, we expect 38 pe for such a signal, well above the requirement. 496 APD arrays are required for the near detector and about 12,000 are used in the far detector design.

The signals from the APDs are processed by front-end electronics (FEBs) which operate in continuous baseline subtraction digitization mode while sampling each channel every 500 ns [2]. 64 FEBs are fed to a Data Concentrator Module which packages and passes the data in 50 μs blocks to a processing buffer nodes. The data is then buffered at the buffer nodes for 20 seconds at which point a software trigger may be issued to record available data in a specified window.

Figure 5. NOvA prototype near detector on surface.

4.2 Current Status.

Far detector building at Ash River, Minnesota is complete. The module factory at the University of Minnesota is in full production. The far detector construction is underway. On September 10, 2012, the first 32-plane block was assembled and put in place. Excavation of the underground cavern for the near detector is underway.

4.3 Prototype Detector.

A prototype near detector on surface (NDOS) has been completed. A picture of NDOS is shown in Figure 5. This prototype has been taking data since October 2010.

Building the NDOS fully exercised the quality assurance/quality control (QA/QC) techniques. This process revealed cracks in ~20% of the manifold covers. These covers have been repaired and a new more robust design that is used used for the near and far detectors.

Oil work at NDOS gained us experience in the filing process. Some internal module obstructions were observed during filling; the causes of these has been resolved. NOvA has currently taken possession of around 100,000 gallons of the oil that will be used for the far site.

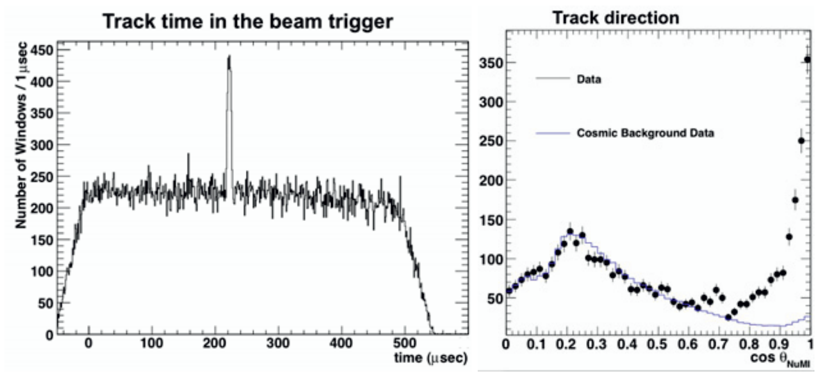
NDOS fiber handling allowed us to overcome tangling problems related to spooling techniques. We have also learned to measure the fiber performance in realtime as modules are strung. About 50% of the required fiber is already received.

Surface cleanliness and sealing issues have led to many of the NDOS APDs becoming unusably noisy. 274 installed unit have been removed from the detector for cleaning and study. New surface coatings and installation techniques were designed.

In addition, a new APD drying system was installed at NDOS and successfully tested. It will protect APDs from condensation in case of sealing problems.

Analysis of the data from NDOS is in progress. A full suite of available Monte Carlo (masked to behave like our prototype) together with tracking on real data has allowed us to begin to calibrate and reconstruct.

NDOS has collected $5.6{\times}10^{19}$ protons on target (POT) worth of data in reverse horn current beam and $8.4{\times}10^{18}$ POT in forward horn mode from NuMI. Analysis of this sample has yielded 1254 candidate neutrino events with 108 expected cosmic background events. Figure 6(a) shows a peak in the track timing distribution right where the NuMI beam is expected. In Figure 6(b) one can see the excess of tracks pointing back to the NuMI source over the out-of-time cosmic background [3]. Similar distributions have been seen in a Booster neutrino sample of 222 event (with 92 expected background events) from $3{\times}10^{19}$ POT [4].



(a) Track time distribution in the Beam events.

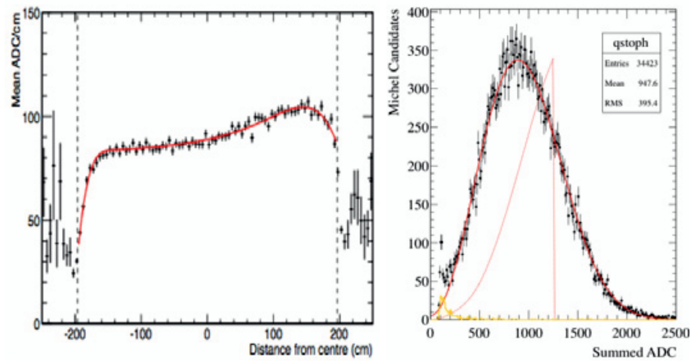
(b) Track direction distribution for both Beam and Beam-off events.

Figure 6. Observation of NuMI neutrino events in NDOS.

Additional studies have been performed to understand the energy deposited in the detector and its cell by cell calibrations. Figure 7(a) shows the mean ADC value as a function of the distance from the center of the cell from a cosmic muon sample [5]. A sample fit which could be used to calibrate the detector response is shown. Figure 7(b) shows a sample Michel electron distribution which can be compared against expectation from simulation to provide an electromagnetic energy calibration [6].

5 Conclusion

The NOvA NDOS is taking and analyzing data now. This surface prototype has proved invaluable to all aspects of the experimental program, providing critical feedback for design enhancements and operational experience. A large value for θ_{13} that was discovered recently by several experiments is very encouraging for the long term physics reach of NOvA and open the opportunity to make real contributions in understanding the neutrino. The first block of the far detector is built. Data taking will begin in 2013, with the detector hall construction nearly complete and expected beam upgrades running on time. The support for NOvA continues to grow with the collaboration now consisting of 140 physicists from 26 institutions in 4 different countries.



(a) Attenuation from muons [5]. (b) Michel spectrum [6].

Figure 7. Preliminary analysis of events from the NuMI source and cosmic data in NDOS.

References

[1] J. K. Anderson et al., FERMILAB-DESIGN-1998-01 (1998).
[2] Feldman G, et. al. 2007 *NOvA Technical Design Report*
[3] Betancourt M 2011 *Internal Nova Document NOVA-doc-5874*
[4] Johnson C 2011 *Internal Nova Document NOVA-doc-5873*
[5] Backhouse C 2011 *Internal Nova Document NOVA-doc-5931*
[6] Messier M 2011 *Internal Nova Document NOVA-doc-6023*