NOνA: Physics, Status and Technology

T. E. Coan*

Physics Department, Southern Methodist University,
Dallas, TX 75275, USA
E-mail: coan@smu.edu
www.physics.smu.edu

NOvA is a long-baseline neutrino oscillation experiment that uses the upgraded NuMI beamline at Fermilab as its neutrino source and a 14 kiloton surface detector in northern Minnesota as its primary neutrino detector to measure a broad range of quantities in neutrino oscillation physics: θ_{13}, θ_{23}, $|\Delta m^2_{23}|$, the CP violating phase δ and the neutrino mass hierarchy. The experiment's physics scope and its detectors' novel design as low-Z, high granularity tracking calorimeters are described, along with its front-end readout and data acquisition systems. NOvA's schedule and initial performance are also presented.

Keywords: NOνA; neutrino oscillation; mass hierarchy; CP violation, NuMI.

1. Introduction

The NumI Off-axis ν_e Appearance (NOνA) experiment is a long baseline neutrino oscillation experiment well under construction at Fermilab and northern Minnesota whose primary physics goals are the measurements of 4 neutrino reactions: $\nu_\mu \to \nu_e$ (plus the CP conjugate reaction) and $\nu_\mu \to \nu_\mu$ (and its CP conjugate reaction). This permits the determination of the PMNS mixing angles θ_{13} and θ_{23}, and provides information on the neutrino mass hierarchy as well as the amount of CP violation in the neutrino sector.

NOνA relies on an upgraded NuMI beamline and an experimental configuration of two nearly identical detectors to reduce systematic uncertainties associated with beam flux, neutrino cross-sections and event selection efficiencies. The smaller 0.3 kton near detector (ND) is 1 km from the neutrino source in a new underground cavern at Fermilab, while the massive 14 kton far detector (FD) is surface-sited 810 km away in northern Minnesota to exploit the matter effect.

*For the NOνA collaboration.

2. NuMI Upgrade

In the post-Tevatron era the FNAL accelerator complex of Booster, Recycler and Main Injector (MI) have been upgraded to decrease the repetition time of the MI from 2.2 s to 1.33 s. This has been accomplished primarily by converting the 8 GeV Recycler, now longer need as an anti-proton accumulator, to a proton storage ring. The upgrade calls for 12 Booster batches to be slipped stacked into 6 for single turn extraction into the MI. This injection is in parallel with the previous MI acceleration cycle, reducing the overall cycle time for delivering 120 GeV protons to the NuMI target. The upgrade calls for the protons per spill to increase slightly to 4.9×10^{13}, corresponding to 6×10^{20} protons-on-target (POT) per year. The overall effect is to raise the NuMI beam power to 700 kW, substantially greater than the 400 kW design power for MINOS. NuMI commissioning is expected to take a year or so before the design power is reached with the the first year maximum power expected to be ~ 500 kW

NOνA uses the off-axis beam technique that exploits the kinematics of two-body decays whereby the energy of the 2 decay products of a pion (or kaon) is strongly correlated with their decay angle in the lab frame. The overall effect is to produce neutrinos of energy largely independent of the parent hadron. For NOνA's 14 mrad off-axis angle this produces a narrow beam centered at 2 GeV. Such a beam is strongly favored over an on-axis beam since the flux of electron neutrinos with an energy corresponding to the first oscillation maximum for a detector of 810 km flight path is much greater for an off-axis beam. This is shown in Figure 1. Additionally, feed-down from higher energy neutral current events to the 1-3 GeV energy range of interest for oscillation physics is much reduced using an off-axis beam.

Other modifications, besides those to the accelerator complex, include making NuMI's 2.0 interaction length graphite target more robust since it no longer needs to live inside the first focusing horn. Figure 2 shows the new target.

3. Detectors

NOνA's FD and ND are designed to be mechanical and and electronic copies of one another and are configured as low-Z tracking calorimeters.[1] The FD is a parallelepiped 15.5 m $\times$ 15.5 m $\times$ 60 m long composed of 896 planes of extruded PVC, arrayed in 28 blocks of 32 planes each, that alternately run in the horizontal and vertical directions. Each plane has 384 identical paral-

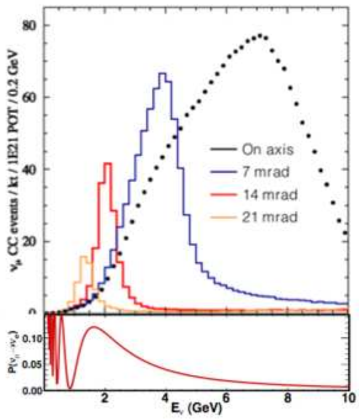

Fig. 1. The 14 mrad off-axis NOνA beam spectrum peaked at 2 GeV, well matched to the first oscillation peak for a detector baseline of 810 km as shown in the bottom graph.

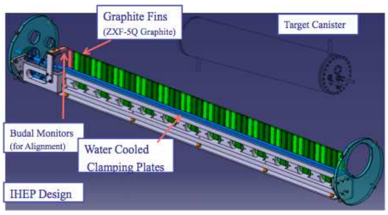

Fig. 2. The NOνA target. Beam passes through the graphite fins on upper part of the of the rail.

lel cells of cross-section 4 cm $\times$ 6 cm for a total channel count of 344 064. All cells are filled with liquid scintillator whose primary fluor is pseudocumene at a concentration of 5% by weight and making the overall FD 65% active. Each plane is only $0.18X_0$ thick and the Moliere radius $R_M = 9.8$ cm (2.5 cells). The high granularity of the detector aids in distinguishing between electron and photon induced showers.

Inside each cell is a looped green wavelength shifting (WLS) fiber that captures and converts scintillation light before transporting it along both of its portions to a single pixel of a 32-channel avalanche photodiode (APD). Each APD is run at a gain of 100, cooled to -15 C to reduce dark current and mounted on just one side of a cell. Since the FD is surface sited with a modest overburden, the overall cosmic rate is expected to be ~ 200 kHz.

As of mid-September 2013, 4.2 blocks of the eventual 28 FD blocks are fully instrumented with the balance due to be completed by May 2014. Figure 3 shows a real cosmic muon showering in the detector while Figure 4 shows the measured zenith angle distribution for cosmic muons, including the expected falloff at small zenith angle due to acceptance effects.

The 100 m underground ND is a 20 000 channel scaled down version of the FD and shaped like a 4.2 m $\times$ 4.2 m $\times$ 14.3 m parallelepiped. It is configured as 8 blocks of 24 planes each plus a muon range stack at its back

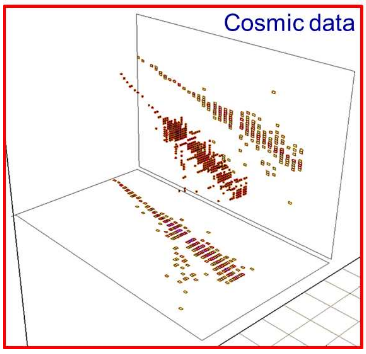

Fig. 3. A cosmic muon showering in the FD and showing the distribution of hit cells in the two orthogonal readout planes.

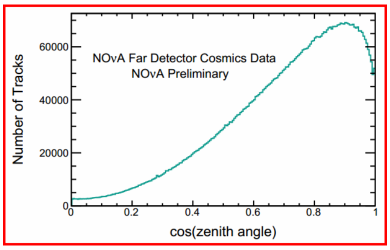

Fig. 4. Zenith angle distribution of cosmic muons measured in the partially instrumented FD.

comprised of iron plates interleaved with vertical and horizontal detector planes. Aside from its smaller size, its cells, readout electronics and data acquisition system are identical to the FD's. At least half of the ND is due to be completed by early 2014.

4. DAQ System

The NOνA data acquisition (DAQ) system is designed to accept and process three broad classes of events:

- *Neutrino beam events.* Activity in the detector correlated in time with the 10 μs NuMI beam spill produced every 1.3 s is considered a potential neutrino event and recorded.
- *Calibration events.* Detector activity sampled in time intervals out of synchronization with the beam spill but at a rate 100x greater than the spill rate.
- *Miscellaneous physics events of interest.* Detector activity exclusive of beam spill and calibration triggers that is consistent with such diverse phenomena as magnetic monopoles, supernovae, etc. are recorded.

Events are captured and and recorded by front-end electronics that read out continuously with no dead time and that are "triggerless" in the sense that no strobe or gate signals them to be active. Data is sent to a downstream buffer farm that holds it for a minimum of 20 seconds while waiting for either a spill trigger or a decision that some interesting event has occurred. The spill trigger is a signal sent from the FNAL accelerator system to the FD via internet and consists of a time stamp and subsequent time interval.

A block diagram of the the NOνA DAQ system is shown in Figure 5. The continuous data flow begins in the upper left with custom electronics labeled Front End Boards (FEBs). Each 32 channel FEB is connected to a single 32-channel APD and consists of a custom ASIC for shaping and amplification of the APD signal, plus multiplexing circuitry that routes the signals to a bank of ADCs for digitization. An FEB's FPGA then processes the digitized signal to extract pulse height and timing information, and to pack the data into 50μs long time intervals.

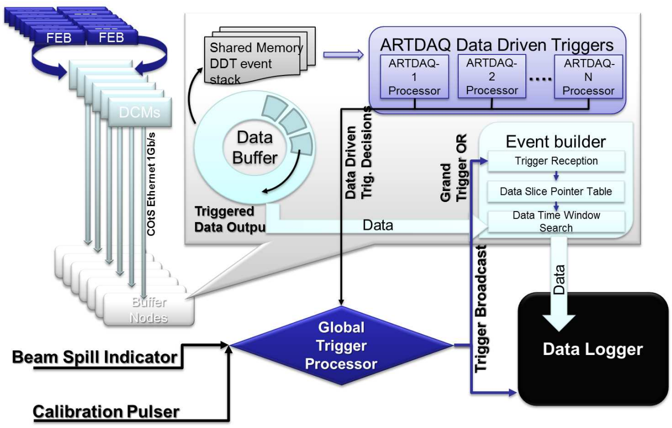

Fig. 5. Block diagram of the NOνA DAQ system.

Data is then transferred to a custom data concentrator module (DCM) that communicates with up to 64 individual FEBs via a point-to-point serial data link. A DCM concatenates the data from its set of FEBs into time intervals of 5 ms duration before transferring it to a downstream buffer node in the buffer farm, a set of 200 commodity servers. A DCM is also responsible for programming, configuring and monitoring its set of FEBs.

Data transfer from the DCMs to the buffer nodes works in a round robin fashion so that all detector data in a given 5 ms time interval resides on a single buffer node with the depth of the entire buffer farm equal to 20 s. A Global Trigger Processor (GTP) provides an external trigger to the buffer nodes in the form of a start time and time window derived from the

NuMI beam spill signal or calibration triggers designed to randomly sample data. Only buffered data satisfying the GTPs timing trigger is written downstream to the Data Logger, a single commodity server, that eventually writes it to disk for offline analysis.

5. Physics Reach

Measurement of the two "appearance" reactions, $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, illustrates an example of NOνA's physics reach. Since the NuMI beam is narrowly peaked at 2 GeV, measuring these two reactions corresponds to measuring two appearance probabilities, $P(\nu_e)$ and $P(\bar{\nu}_e)$, which produces a point in the bi-probability plot. This is shown in Figure 6 for some sensible assumptions of mixing parameters and 6 years of total running at 6.0×10^{20} POT/yr. The two ellipses correspond to the two possible values of the mass hierarchy (solid blue is the normal hierarchy) and the position of the point $(P(\nu_e), P(\bar{\nu}_e))$ on a given ellipse depends on the value of δ. For the test case of the starred point shown (normal hierarchy and $\delta = 3\pi/2$), the 1σ (dashed circle) and 2σ (solid circle) sensitivities are shown. Hence, the inverted mass hierarchy would be excluded by at least 2σ for this scenario.

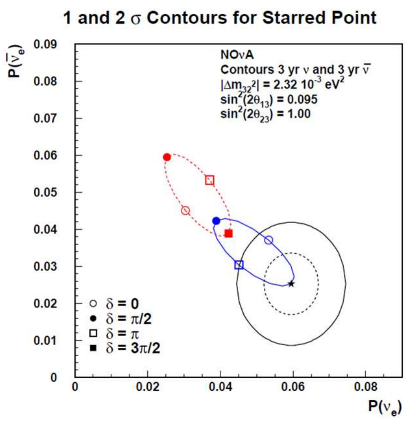

Fig. 6. General measurement scheme for NOνA's appearance reactions at 2 GeV for sensible assumptions of mixing parameters. All possible values for $P(\nu_e)$ and $P(\bar{\nu}_e)$ are shown. See text for explanation.

Figure 7 shows the significance of determining the mass hierarchy as a function of the CP phase angle δ for representative values of mixing parameters. Figure 8 shows the corresponding plot including T2K data and the effect of its shorter baseline that de-emphasizes the matter effect.

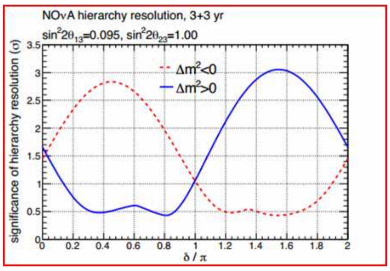

Fig. 7. NOνA significance for resolving the mass hierarchy as a function of δ for sensible assumed values of $\sin^2(2\theta_{13})$ and $\sin^2(2\theta_{23})$. A total of 6 years of running evenly divided between ν and $\bar{\nu}$ and with an integrated 3.6×10^{21} POT is also assumed. The solid blue line is for the normal hierarchy.

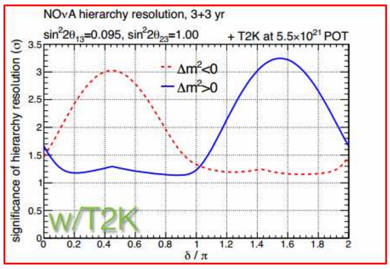

Fig. 8. Similar to Figure 7 but including 5.5×10^{21} POT of T2K $\nu_\mu \to \nu_e$ running. The shorter baseline of T2K helps in certain hierarchy/δ scenarios.

6. Summary and Outlook

NOνA is making excellent progress and is expected to be fully constructed by late Spring 2014. The NuMI beam is back and NOνA will begin collecting neutrino data in Fall 2013. Its tentative run plan is to run first in neutrino mode for 3 years and then switch to anti-neutrino running for 3 more years. NOνA has good sensitivity for measuring θ_{13}, θ_{23}, $|\Delta m^2_{23}|$ and the CP violating phase δ. A six-year run will allow NOνA to unambiguously resolve the mass hierarchy at the 95% C.L. for at least a third of the possible values of δ.

Acknowledgments

The author acknowledges support from the US Department of Energy under contract DE-FG02-13ER41977.

References

1. D.S. Ayres *et al.*, FERMILAB DESIGN-2007-01 (2007).