FERMILAB-CONF-12-641-PPD

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B Proceedings Supplement 00 (2013) 1–6

Nuclear Physics B Proceedings Supplement

NOvA: Current Status and Future Reach

Mathew Muether

Fermi National Accelerator Lab, Neutrino Department, P.O. Box 500 MS-220, Batavia, IL 60510 USA

Abstract

NOνA, the NuMI Off-Axis ν_e Appearance experiment will study $\nu_\mu \rightarrow \nu_e$ oscillations, characterized by the mixing angle θ_{13}. A complementary pair of detectors will be constructed ~14 mrad off beam axis to optimize the energy profile of the neutrinos. This system consists of a surface based 14 kTon liquid scintillatior tracking volume located 810 km from the main injector source (NuMI) in Ash River, Minnesota and a smaller underground 222 Ton near detector at the Fermi National Accelerator Laboratory (FNAL). The first neutrino signals at the Ash River site are expected soon after the completion of 2012 Fermilab accelerator upgrades. In the meantime, a near detector surface prototype has been completed and neutrinos from two sources at FNAL have been observed using the same highly segmented PVC and liquid scintillator detector system that will be deployed in the full scale experiment. With the recent measurements of θ_{13} as input, updated sensitivities of NOνA's capability to ultimately determine the ordering of the neutrino masses and measure CP violation in neutrino oscillations will be provided. Additionally, design and initial performance characteristics of the surface prototype system along with implications for the full NOνAprogram will be presented.

Keywords: neutrino oscillations, neutrino detector technology
PACS: 13.15.+g,
PACS: 14.60.Pq

1. Introduction

NOνA, the NuMI Off-Axis ν_e Appearance experiment will study $\nu_\mu \rightarrow \nu_e$ oscillations at a baseline of 810 km (L/E of 400 km/GeV) beginning in 2013, at which point it will become the flagship experiment for Fermilab. With the recently measured value of θ_{13} [1], NOνA will have the reach to determine the ordering of the neutrino masses and constrain the CP violating phase, δ [2]. Additionally, NOνA will study the differences in oscillations of neutrinos and antineutrinos, as well as make a precision measurement of θ_{23} by observing the muon neutrino disappearance.

Achieving these goals requires three main components: a far detector with 14 kTons of material capable of suppressing ν_μ charge current (CC) and neutral current (NC) backgrounds at the 99% level and providing good ν_e detector efficiencies [2], a functionally identical near detector to characterize the beam at the source (rate shown in Figure 1), and an upgrade 700 kW neutrino beam line. This paper will focus on the experimental design of NOνA, present preliminary data from a running prototype, update the project status, and provided current expected physics sensitivities.

2. Experimental design

Each component of the NOνA design is described.

2.1. Beam

To achieve the goal of the NOνA project, detectors will be placed 14 mrad off-axis to the primary direction of the NuMI (Neutrinos from the Main Injector) source (need reference). As shown in Figure 2, the ν_μ flux near the first $\nu_\mu \rightarrow \nu_e$ oscillation maximum at around 2 GeV

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

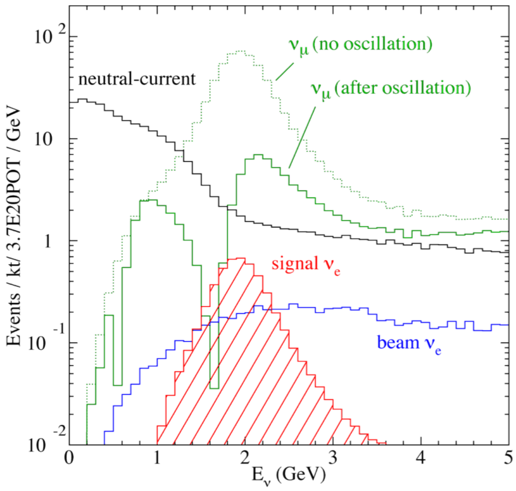

Figure 1: Expected raw signal and background rates for the NOνA far detector. Interaction spectra at 810km, 14 mrad off axis. Oscillations parameters: $\delta m^2 = 2.5\text{x}10^{-3}$ eV^2, $sin^2(2\theta_{13})$=0.01 [2].

is optimized at this angle [2]. The off-axis beam also reduces high energy neutral current background events. To accommodate the needs of the experiment, the NuMI beam power is being doubled to 700 kW during the shutdown of the accelerator from March to May 2013.

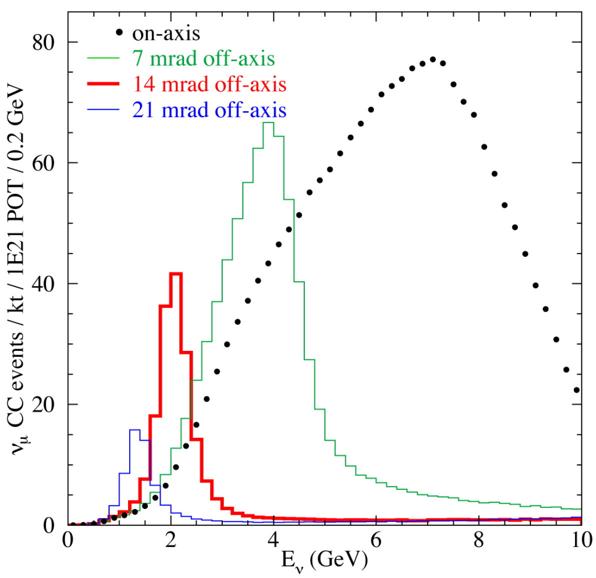

Figure 2: ν_μ CC energy distribution for off-axis angles with medium energy tune [2].

2.2. Detector Summary

The NOνA detector system consists of a complementary pair of detectors. Both detectors will be highly segmented tracking calorimeters built entirely from low Z (~0.15 radiation lengths per layer) PVC, glue, and mineral oil based liquid scintillator with a 65% active volume [2]. The far detector will be a surface based 14 kTon volume located 810 km from NuMI in Ash River, Minnesota with about 10 radiation lengths of barite overburden. A smaller 300 Ton unit will be built 1.1 km from the source at Fermilab in a 105 meters deep underground cavern. Additionally, a 222 ton prototype detector is already in operation on the surface at Fermilab. The full set of detectors is shown in Figure 3.

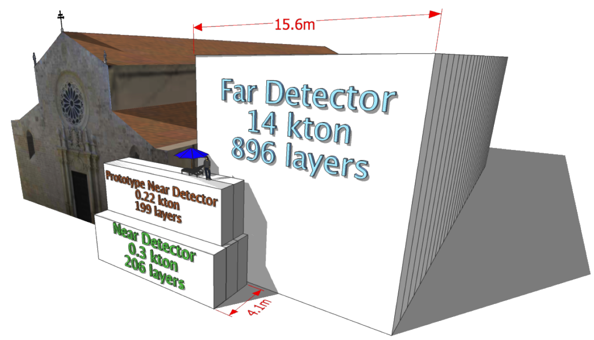

Figure 3: Image of the NOνAdetectors shown against the the Cathedral of Otranto.

2.3. Detector modules

The NOνA detector is built up from modules of extruded TiO_2 loaded PVC cells [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 together to produce a sealed module of 32 cells. In the near detector, the modules will be 4.2 m long while far detector modules are 15.6 m long. These modules are glued together into alternating planes of horizontal or vertical orientation to create self-supporting 32 layer blocks. ~360,000 cells make up the 14 kTon far detector.

Internal to each cell is a 0.7 mm diameter looped fiber routed to an optical connector. The fiber shifts the light collected in the scintillator to 490-550 nm [2]. The fiber ends are routed through the manifold covered to an optical connector where they are available for single sided readout. ~11,500 km of fiber is needed for both the far and near detectors.

Once in blocks and positioned, modules are filled with a "home brew" of 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]. The 14 kTon far detector will use over 10.5 million liters of liquid scintillator.

2.4. Detector Readout

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 in controlled environmental conditions at -15 °C with a gain of 100. For NOνA, a 38 photoelectron (pe) signal from a minimum ionizing particle at the far end of a far detector sized module is expected. 12000 APD arrays are required for the near and 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].

2.5. DAQ

64 FEBs are fed to a Data Concentrator Module which packages and passes the data in 50 μs blocks to a processing farm. The data is then buffered at the farm for several seconds at which point a software trigger may be issued to record available data in a specified window. Beam spill and data driven triggers will be available. The entire system is synchronized to GPS and phase locked to its one pulse per second signal. Internal clocking is also available [2].

2.6. Expected Event

With this setup, NOνAwill have sensitivities to ν_μ charge current quasi-elastic events shown in Figure 4 with a associated Michel electron from the stopping muon and proton recoil inset, ν_e charge current showers, and neutral current event shown in Figure 4 with a characteristic gap form a photon prior to conversion.

3. Results from the prototype near detector on the surface (NDOS)

Six blocks were constructed along with a 1.7 m muon ranger (Fig. 5) for NDOS. Building the NDOS fully exercised the quality assurance/quality control (QA/QC) techniques in preparation for full production running for the far detector and has been invaluable in understanding production, installation, integration and operations. This detector has been collecting cosmic and neutrino data since October 2010. An additional feature of the NDOS is that it is exposed to both the 0.4 Hz NuMI (110 mrad off-axis) and 1.2 Hz Booster neutrino (on-axis but rotated) beam lines at Fermilab. Prior to the shutdown, 500 microsecond trigger windows were collected from both beams.

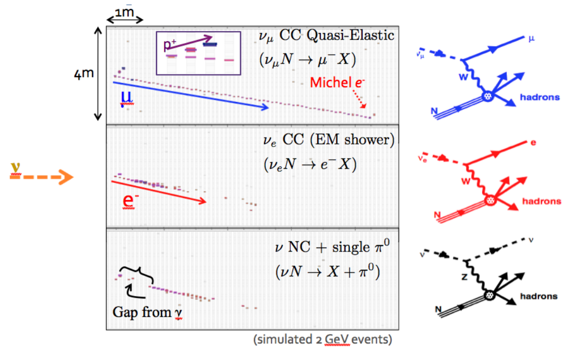

Figure 4: Example of expected NOνAevent topologies.

Figure 5: Photograph of the NOνA Near Detector On the Surface.

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 5.6×10^{19} protons on target (POT) worth of data in reverse horn current beam and 8.4×10^{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 shows an excess of tracks pointing back to the NuMI source over the out-of-time cosmic background and Figure 7 shows this excess as a function of time in the trigger window [4]. Similar distributions have been seen in a Booster neutrino sample of 222 event (with 92 expected background events) from 3×10^{19} POT [5].

Additional studies have been performed to understand the energy deposited in the detector and its cell

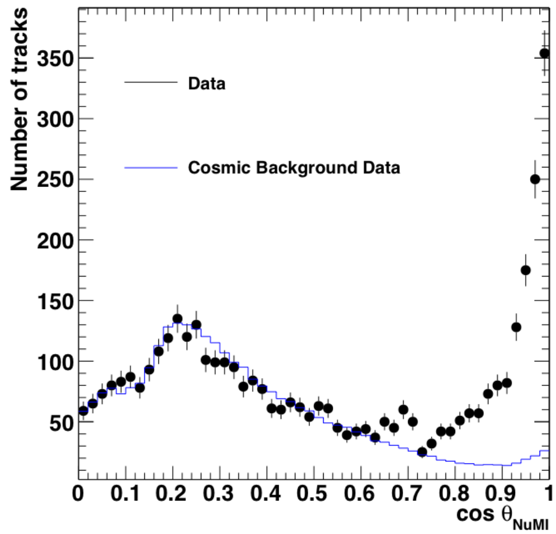

Figure 6: Angular track distribution [4].

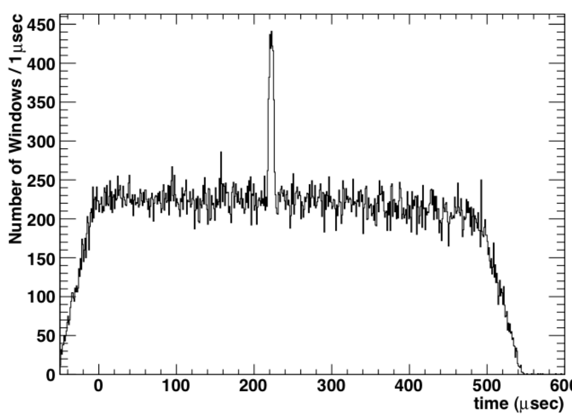

Figure 7: Timing activity [4].

by cell calibrations. Figure 8 shows the mean ADC value as a function of the distance from the center of the cell from a cosmic muon sample [6]. A sample fit which could be used to calibrate the detector response is shown. Figure 9 shows a sample Michel electron distribution which can be compared against expectation from simulation to provide an electromagnetic energy calibration [3].

4. Project status

Module production occurs at an undergraduate driven factory at the University of Minnesota. The factory is

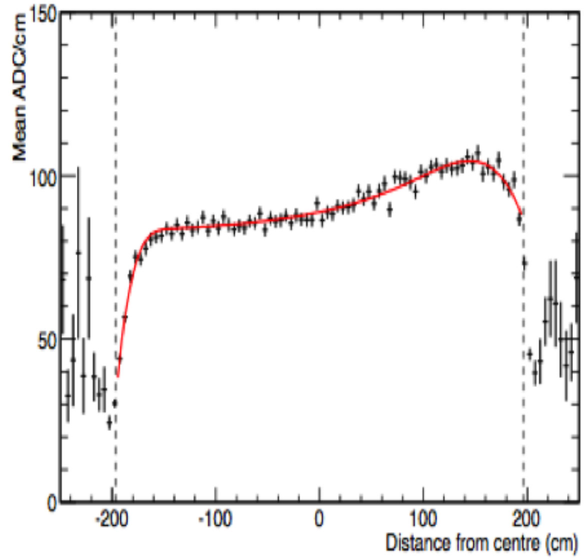

Figure 8: Attenuation from muons [6].

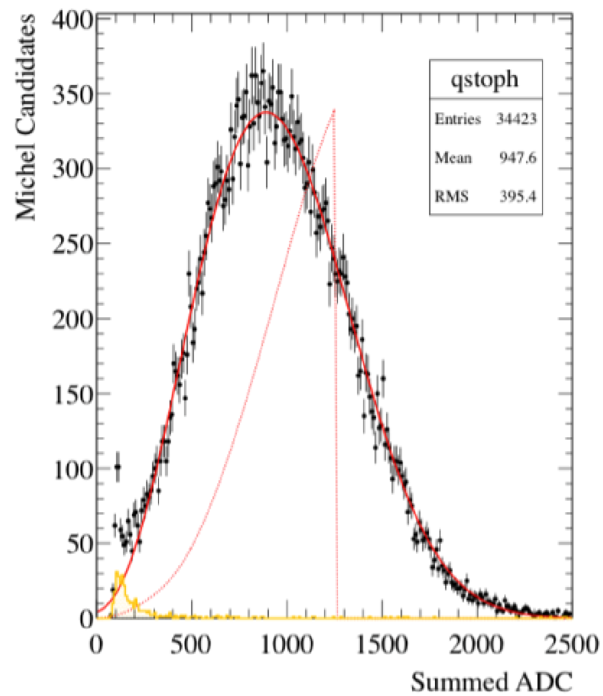

Figure 9: Michel spectrum [3]

reaching full production levels now, necessary to keep pace with the construction of the detector at Ash River.

Beneficial occupancy of the far detector facility was obtained in April 2011, and construction of the first blocks is underway. The first block was positioned using the block pivoter on September 10, 2012 and 5 blocks have been placed to date with 1 block being built every 2 weeks. This construction is available via webcam for public viewing [7].

Excavation of the underground cavern for the near detector completed in November 2012 following the beam shutdown and outfitting is on schedule to be ready for near detector blocks in Summer 2013.

The ANU beam upgrades are also progressing. Work is ongoing to turn the Recycler from antiproton to proton ring, shorten Main Injector cycle from 2.2 seconds to 1.33 seconds, and overhaul the NuMI target station for 700 kW running. This work is scheduled to be complete by spring 2013.

5. Physics Sensitivities

Once complete, the NOνAdetector will be a powerful machine with sensitivity to many neutrino phenomenon as presented in this section. The sensitivities in the section assume $\sin^2 2\theta_{13}$=0.095, optimization for 4 percent oscillation probability, 10 percent uncertainty on backgrounds, 41 percent ν and 48 percent anti-ν signal efficiency [8]. Also assumed is the the ramp-up in detector mass and beam power and resulting exposure shown in Figure 10.

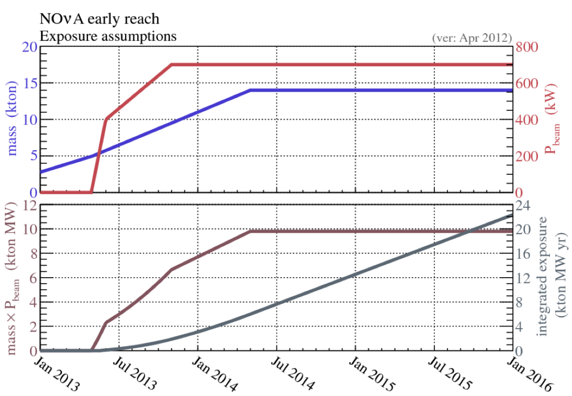

Figure 10: Expected detector mass, NuMI power and exposures [8].

With these assumptions and starting running in ν mode, NOνAexpects to achieve an 5σ observation of $\nu_\mu \rightarrow \nu_e$ in the first year of running if neutrinos follow the normal hierarchy [8]. This is possible in part to the design of the detector which allows simultaneous running and construction. Anti-ν_e running could commence at any time to optimize other scenarios of interest. Figure 11 show the details of the $\nu_\mu \rightarrow \nu_e$ sensitivities with respect to time.

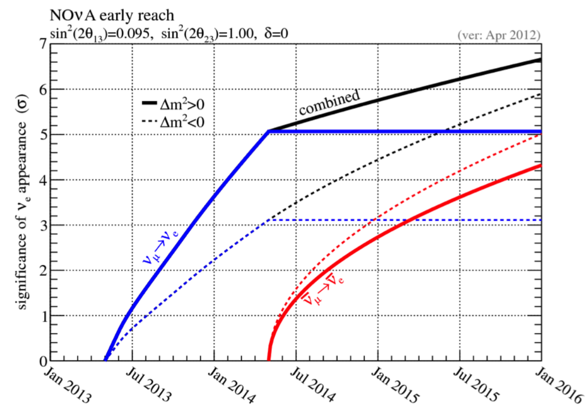

Figure 11: Electron neutrino appearance sensitivities [8].

For additional measurements NOνA will rely on the the comparison of 2 GeV $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu_\mu} \rightarrow \bar{\nu_e}$ probabilities. Figure 12 demonstrates the principle by which NOvA determines the mass hierarchy, measure the CP phase, and isolate the sign of θ_{23} [8]. The ellipses show the δ cp values and choice of hierarchy that could yield from the oscillation probability measurements given the specified $sin^2(2\theta_{13})$ value. The blue curves are for the normal hierarchy and the red curves are for the inverted hierarchy. On each ellipse, the choice of the CP phase delta varies as one moves around the ellipse as indicated by the symbols. If NOνA makes a measurement of oscillation probability in each neutrino mode (after 3 years of running in each mode) that yields the starred point with 1- and 2-sigma contours, the hierarchy is resolved, CP phase is constrained for particular values of delta at the 2-sigma level, and θ_{23} sign is suggested. This assumes maximal mixing in the θ_{23} octant. This leads to sensitivities for the mass hierarchy determination, CP violation phase, and θ_{23} octant as shown in Figures 13,14,15 [8].

6. Conclusion

NOνA far detector construction is underway and first data is expected in spring 2013 long with the NuMI 700kW upgrades. Near detector excavation is complete and outfitting is scheduled to complete in summer 2013. The NOνA NDOS is taking and analyzing data now. This surface prototype has proved invaluable to

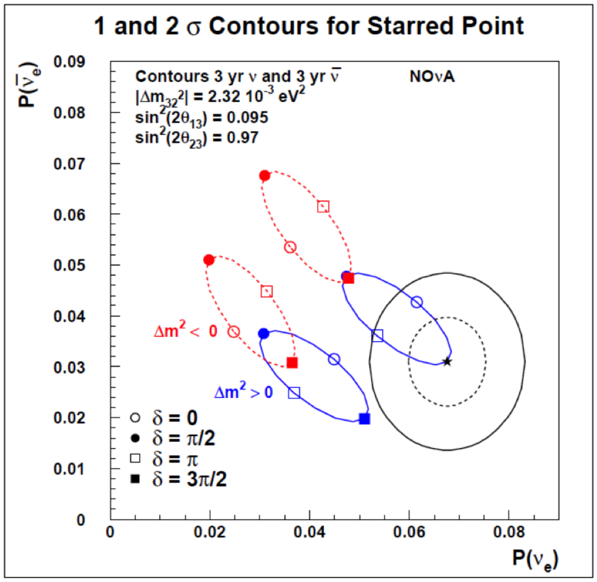

Figure 12: Biprobability plots described in text [8].

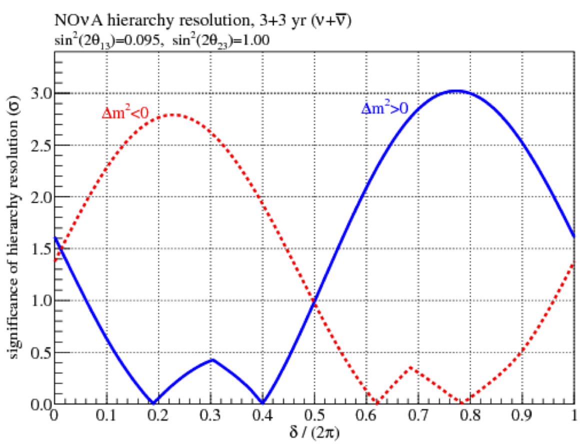

Figure 13: NOνA mass hierarchy sensitivites [8].

all aspects of the experimental program, providing critical feedback for design enhancements and operational experience. The recently measured large value for θ_{13}, is very encouraging for the long term physics reach of NOνA and opens the opportunity to make real contributions in understanding the neutrino especially to mass ordering, CP violating phase and θ_{23} octant. The support for NOνA continues to grow with the collaboration now consisting of 150 physicists from 33 institutions in 6 different countries.

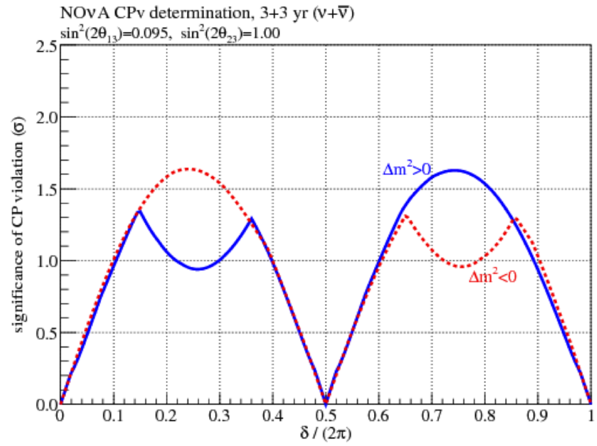

Figure 14: NOνA δ CP sensitivites [8].

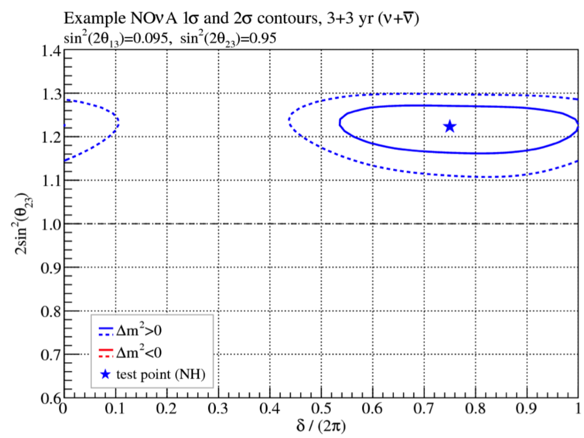

Figure 15: NOνA θ_{23} sensitivities [8].

References

[1] Abe K, *et al.* 2011 *Indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam, Preprint* arXiv:1106.2822 [hep-ex]

[2] Feldman G, *et al.* 2007 *NOvA Technical Design Report*

[3] Messier M 2011 *Internal Nova Document NOVA-doc-6023, Low energy event analysis: Michel electrons*

[4] Betancourt M 2011 *Internal Nova Document NOVA-doc-5874, NuMI Events in NDOS*

[5] Johnson C 2011 *Internal Nova Document NOVA-doc-5873, Booster Neutrinos in the Nova IPND*

[6] Backhouse C 2011 *Internal Nova Document NOVA-doc-5931, Cosmic rays for detector calibration*

[7] NOvA Far Detector Live Webcam 2012, *http://www.fnal.gov/pub/webcams/nova_webcam/*

[8] Feldman G, 2012 *Internal Nova Document NOVA-doc-7393, NOvA sensitivity plots*