NOvA: Present & Future

Gavin S. Davies
Iowa State University

for the NOvA Collaboration

DPF 2011: Brown University, Providence, RI

August 9th – 13th 2011
The NOνA Collaboration

\textbf{NuMI* Off-axis }\textbf{ν}_e Appearance

24 Institutions
110 physicists
4 countries

ANL, Athens, Caltech, Institute of Physics of the Czech Republic, Charles University, Czech Technical University, FNAL, Harvard, Indiana, Iowa State, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Twin Cities, INR Moscow, South Carolina, SMU, Stanford, Tennessee, Texas/Austin, Tufts, Virginia, WSU, William and Mary

* Neutrinos at the Main Injector
The NOνA Experiment

Physics Goals:

- Search for oscillations
  \(\nu_\mu \rightarrow \nu_e\) and \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\)
- Measure \(\theta_{13}\)
- Constrain \(\delta_{CP}\)
- Determine neutrino mass hierarchy
- Precision measurements of \(\Delta m^2_{32}, \theta_{23}\)

- 810 km baseline from Fermilab to Ash River, MN
  - Near and Far Detectors
- 700 kW upgraded NuMI beam
- Off-axis (14 mrad) detectors
Off-axis

- Medium Energy NuMI beam favoured
- 14 mrad off-axis
- Essentially all pion decays yield neutrinos in 1-3 GeV range
  - Narrow band beam peak at 2 GeV
  - Near oscillation maximum
  - Reduction of NC backgrounds
NOvA Detectors

Far Detector
- 928 Planes (15.6 m x 15.6 m)
- 14kTon
- ~360000 cells
- Cosmic Ray Muon Rate: ~200 kHz (2-3 m overburden)
- Neutrino Rate:
  - 1400 $\nu_e$ beam events/year

Near Detector
- 196 Planes (2.9 m x 4.2 m)
- + 10 Steel/Scint Plane Pairs (“MuonCatcher”)
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
- ~50 Hz (105 m overburden)
- Neutrino Rate:
  - 10 $\mu$s spill duration every 1.33 s
  - 30 neutrino events/spill

Far Detector superimposed in SoldierField

 Beam direction

Far Detector

Near Detector
Detector Technology

- 16-cell PVC extrusions (15% TiO$_2$). Each NOvA cell:
  - 3.9 cm x 6.0 cm x 15.6 m (FarDet)
  - ~90% reflectivity at 430 nm
  - 8 reflections on average
- ~360,000 cells (Far), ~16,000 (Near).
- 32 in a sealed module. Alternating X/Y planes.
- Filled with liquid scintillator
  - mineral oil + ~5% pseudocumene
- Read out by wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD)

See Xinchun Tian's talk (Friday, 8:20am) for details of the NOvA Data Acquisition System
NOvA is sensitive to electron neutrino appearance down by an order of magnitude at 90% CL.

Sensitivity to $\sin^2(2\theta_{13})$ after 3 years each of running $\nu$ and $\bar{\nu}$ beams

Contours for different beam upgrades also shown

$18 \times 10^{20}$ POT in each neutrino and antineutrino mode
Comparing to recent results

Overlay of MINOS and T2K allowed regions

90% CL Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

$L = 810 \text{ km, 15 kT}$
$\Delta m^2 = 2.4 \times 10^{-2} \text{ eV}^2$
$\sin^2(2\theta_{23}) = 1$

3 years at 700 kW, 1.2 MW, and 2.3 MW for each $\nu$ and $\bar{\nu}$

$\Delta m^2 > 0$

$\Delta m^2 < 0$

$\delta_{CP} (\pi)$

arXiv:1108.0015 (MINOS)
arXiv:1106.2822 (T2K)

R. Patterson
Comparing to global picture

- Recent global fit suggests > 3 σ evidence for non-zero $\theta_{13}$ \cite{G.L. Fogli et al., arXiv:1106.6028}

\[ \sin^2(2\theta_{13}) = 0.098 \pm 0.028, \text{ new reactor fluxes (1σ)} \]

\begin{itemize}
  \item NOvA is sensitive to an order of magnitude better
  \item Recent range indicated by T2K/MINOS results is encouraging for NOvA
\end{itemize}
Constraining $\delta_{\text{CP}}$

Both scenarios: $\delta$ constrained to upper half of plane

1 and 2 $\sigma$ Contours for Starred Point for NOvA

$\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$
$\sin^2(\theta_{23}) = 1$

NOvA 3 years at 700 kW for each $\nu$ and $\bar{\nu}$

MH resolved at 95% CL

$\Delta m^2 > 0$
$\Delta m^2 < 0$

MH not resolved

NOvA 3 years at 700 kW for each $\nu$ and $\bar{\nu}$
Resolving the mass hierarchy

Due to NOvA’s 810 km baseline, matter–induced oscillations affect the oscillation probability by 30%. Matter effects depend on the mass hierarchy sign and change \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) differently.

By running for 3 + 3 years (\( \nu \) and \( \bar{\nu} \)) NOvA may resolve the mass hierarchy if \( \theta_{13} \) is large enough.
Precision measurements of $\Delta m^2_{32}$, $\theta_{23}$

- Sensitivity to $\Delta m^2_{32}$, $\theta_{23}$ after 3 years each of neutrino and antineutrino beam

- Contours for $\Delta m^2_{32}$ at the fit value of $2.35 \times 10^{-3}$ eV$^2$ and different values for $\sin^2(2\theta_{23})$

- NOvA will improve the MINOS measurement of $\Delta m^2_{32}$ and can measure $\sin^2(2\theta_{23})$ to better than 2% due to large detector mass and excellent energy resolution of charged current events ($\nu_\mu + n \rightarrow \mu + p$)

- More precise test whether $\sin^2(2\theta_{23})$ is maximal
ν and $\bar{\nu}$ Disappearance Parameters

- MINOS reported a ~2σ difference between best fit values for $\nu$ and $\bar{\nu}$ disappearance parameters (arXiV:1103.0340)
- NOvA intends to run for 3 years in neutrino mode and 3 years anti-neutrino
- **Top**: MINOS result for anti-neutrino (red) and neutrino (blue) disappearance. The solid (dashed) curves give the 90% (68%) contours.
- If MINOS central values are correct, NOvA will establish the difference with 3σ significance in 2 years, 5σ in 6 years
- **Bottom**: NOvA results after full 6 year run, 3+3 years in neutrinos+ antineutrinos.
Status and Timeline

**NuMI Beam:**
- Upgrade from 320 kW to 700 kW
- In order to achieve this...
  - Accelerator shutdown: March 2012

**Far Detector:**
- Construction starting January 2012
- 50% completion by end of shutdown
- Complete by early 2014

**Near Detector:**
- Cavern excavation during shutdown
- NDOS: Running since October 2010...
Far Detector

Far Detector laboratory complete!
Beneficial occupancy of Ash River laboratory on April 13th 2011
NDOS: Near Detector On the Surface

- Prototype Near Detector collecting data since October 2010
- 6 blocks of 31 alternating orthogonal planes and a muon catcher are installed and filled with scintillator.
- ~50% of the detector is instrumented with electronics
- Gets triggers (500 μs wide) from NuMI (6.4° off-axis) and Booster (~on-axis) beams, plus 10 Hz pulser.

See Susan Lein's talk (Friday, 8:00am) for details of NDOS performance
Lessons Learned

- 22% of module manifolds developed cracks
  - 'Splints' to fix NDOS; Redesign of manifolds
  - Change module pressure testing procedure
- Experience qualifying and filling scintillating oil
- We are using bare APDs
  - Extremely sensitive to all kinds of contamination
  - Cleanliness issues led to noisy channels
  - New installation procedures
  - New APD surface coating under investigation
Cosmic Rays in NDOS

TOP VIEW

SIDE VIEW

Colour shows time
Hits scaled by charge

NOvA - FNAL E929
Run: 11945/6
Event: 309631
UTC Sat Apr 9, 2011
04:35:37.133364000

08.09.2011

Gavin S. Davies, DPF 2011, 9-13 August '11
Cosmic Rays in NDOS

See Nick Raddatz's talk (Friday, 8:40am) for details of particle tracking in NOvA
Calibration

Using cosmic muons as an intra-detector calibration source: Cell-by-cell calibration

**Top left:** Path length-corrected muon response for different distances from fiber end for a single example cell

**Above:** Measured and fitted fiber attenuation for the example cell

**Bottom left:** Muon response after attenuation corrections
Michel Electron Calibration

\[ \chi^2 / \text{ndf} = 169.7 / 303 \]

- Normalization: \( 5696 \pm 87.8 \)
- Muon lifetime (\( \mu \text{sec} \)): \( 2.139 \pm 0.013 \)
- Constant background: \( 1.173 \pm 0.091 \)

Random coincidences
These are clusters that are matched to muons recorded 20 seconds prior to event

Michel spectrum convolved with energy resolution

Michel spectrum with perfect energy resolution

Entries: 34423
Mean: 947.5
RMS: 395.4
Monte Carlo Neutrino Events

\( V_\mu \) Charged-current
Long well-defined muon track, proton is a short track with large energy deposition at the track end.

\( V_e \) Charged –current
Single shower with characteristic e-m shower development.

NC with \( \pi^0 \) in final state
Possible gaps near event vertex, multiple displaced e-m showers.
Neutrinos in NDOS
Neutrinos in NDOS

\[ \nu_\mu + N \rightarrow N' + \nu_\mu + \pi^0 + \pi^0 \text{ candidate} \]

See Jarek Nowak (Thursday, 10:50am) and Minerba Betancourt's (Thursday, 11:10am) talks for details of neutrino interactions and early neutrino data in NOvA's NDOS.
Summary

• NOvA is the flagship project of Fermilab's Intensity Frontier initiative
• Recent results from T2K and MINOS are very encouraging for the NOvA goals
• NOvA is on track to make many important contributions to neutrino physics
  - Measurement of $\theta_{13}$
  - Determination of mass hierarchy
  - More precise measurements of $\Delta m_{32}^2$, $\sin^2(2\theta_{23})$
• Far detector construction is underway.
  - Far detector laboratory complete
  - 14 kt complete by early 2014
• Prototype near detector (NDOS) operational on surface at Fermilab
  - Extremely valuable preparation for construction at Ash River
  - Early look at real cosmic rays and neutrinos
  - Headstart on calibration techniques and physics analyses
• Reminder: 5 more NOvA talks at this meeting...
BACKUP SLIDES
NDOS Location
POT accumulated

NuMI POT vs. Time (for runs with > 1 subrun)

BNB POT vs. Time (for runs with > 1 subrun)
Resolving the mass hierarchy

NOvA + T2K resolves the neutrino mass hierarchy at 95% C.L or better.

Assumes nature has a normal hierarchy.

For $\delta_{CP} > \pi$, NOvA resolves the hierarchy on its own by comparing measurements using neutrino and anti-neutrinos.

For $\delta_{CP} < \pi$, comparison of T2K’s measurement using neutrinos at the first oscillation maximum (limited matter effects) and NOvA’s measurement at the first oscillation maximum (matter effects) helps break the ambiguity in the comparison of NOvA’s neutrino measurement to its anti-neutrino measurement.

95% CL Resolution of the Mass Ordering

3 years for each $\nu$ and $\bar{\nu}$
NOvA at 700 kW, 1.2MW, and 2.3MW
+ T2K 6 years of $\nu$
at nominal, x2, and x4

L = 810 km, 15 kT
$\Delta m^2_{21} = 2.4 \times 10^{-3} \text{ eV}^2$
$\sin^2(2\theta_{23}) = 1$
$\Delta m^2 > 0$
Constraining $\delta_{CP}$

Combining NOvA with T2K in worst case

1 and 2 $\sigma$ Contours for Starred Point for NOvA + T2K

$\Delta m^{2}_{3\tau} = 2.4 \times 10^{-3}$ eV$^{2}$
$\sin^{2}(2\theta_{23}) = 1$

NOvA 3 years at 700 kW
for each $\nu$ and $\bar{\nu}$
+ T2K 6 years

$\Delta m^{2} > 0$
$\Delta m^{2} < 0$