Current Status and Future Reach

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Fermilab

Presented at NOW 2012 for the NOvA Collaboration
Outline

• NOvA – NuMI Off-Axis $v_e$ Appearance Experiment
• Flagship Intensity Frontier experiment at Fermilab when we turn on in 2013
• Project consists of 3 main components: NuMI (Neutrinos from the Main Injector) upgrade, near detector at Fermilab and far detector located in Ash River, MN

This talk will cover:
• Experimental Design
• Data from the prototype near detector
• Current status of the project
• Expected physics sensitivities (NOvA is extremely active right now)
NOvA Program

- Long baseline neutrino oscillation experiment; 14 mrad Off-axis @ L/E ~ 400 km/GeV
- Near detector to characterize the beam
- Far detector for oscillation study

- Physics scope:
  - $\nu_\mu \rightarrow \nu_e$ appearance
    - Measure $\theta_{13}$
    - $\nu$ mass ordering
    - CP violating phase
  - $\nu_\mu \rightarrow \nu_\mu$ disappearance
    - Precision measurement of $\theta_{23}$, $|\Delta m_{23}^2|$ 
  - Cross-sections from near detector
  - Other exotics
# NOvA Collaboration

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| PANJAB UNIVERSITY | |

150+ scientists and engineers from 33 institutions, 6 countries
NuMI Off-axis Beam

- NOvA detectors will be placed 14 mrad off-axis in a narrow band beam
- Increases flux near oscillation maximum
- Reduces high energy NC background events
- Doubling power from 350kW to 700 kW during ongoing shutdown
Design criteria

- Optimized $\nu_e$ detection efficiency for $\nu_e$ appearance measurement.
- Suppression of $\nu_\mu$ CC and NC backgrounds at the 99% level.
- Energy resolution small compared to signal width:
  - Less than 8% for $\nu_e$ Charged Current events
  - Less than 4% for Quasi-Elastic $\nu_\mu$ Charged Current

Interaction spectra at 810km, 14 mrad off-axis. Oscillations: $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$, $\sin^2(2\theta_{33}) = 0.01$
NOvA Detector Suite

Tracking Calorimeters:
- Highly Segmented (Alternating X/Y)
- Low Z (PVC and Oil)
  \(X_0 \approx 40\text{cm}, R_m \approx 11\text{cm}\)
- 65% Active Volume

ND: 1 km from NuMI
- 105 m underground

FD: 810 km baseline
- Surface Detector
- Overburden >10 radiation lengths
Detector Module

- Cross-section of cell 4cm X 6cm
- Runs entire width of detector (15.6m for far detector)
- Filled with scintillator and instrumented with looped wavelength-shifting fiber
- 32 sealed extruded PVC cells
- Both ends of looped fiber routed to an optical connector
- 11,500 km of wavelength shifting fiber in total
- 10.5 million liters of scintillator (or 14 million wine bottles worth)
Detector Readout

• Array of 32 avalanche photo-diodes mated to optical connector
• 85% QE for 520 – 550 nm light.
• Gain of 100 @ 375 volts.
• Controlled environmental conditions
• Actively cooled to -15 C.
• 38 pe signal from MIP at far end of cell (10-12 MeV dep. en)
• Signal digitized by on module front end electronics
• 10-15 pe threshold for data written out
• ~12,000 APDs on FEBs at far detector

Waveform sampling @ 2 MHz
Zero suppression threshold ≈ 35ADC (0.5 MIP)
Data Acquisition

- 64 FEBs feed a Data Concentrator Module which packages and passes the data to a processing farm.
- Data is continuously buffered for several seconds until the arrival of a software spill trigger at which point it is written to disk.
- Beam spill and data driven triggers are available
- System is synchronized by an external timing system to GPS
Expected Event Views

\[ \nu_\mu \text{ CC Quasi-Elastic} \quad (\nu_\mu N \rightarrow \mu^- X) \]

\[ \nu_e \text{ CC (EM shower)} \quad (\nu_e N \rightarrow e^- X) \]

\[ \nu \text{ NC + single } \pi^0 \quad (\nu N \rightarrow X + \pi^0) \]

Gap from \( \gamma \)

(simulated 2 GeV events)
System Prototype

• Prototype Near Detector on the Surface (NDOS) constructed in a mock far detector environment.
• Collecting cosmic and neutrino data since October 2010

• Invaluable in understanding production, installation, integration, and operations.
110 mrad off NuMI axis due to surface position
500 μs wide trigger window @ 0.4 Hz
On-axis for booster (but rotated)
500 μs wide trigger window @ 1.2 Hz
Prototype Events

NuMI neutrino interactions

Similar distributions seen for the booster beam with lower efficiency
NDOS Calibration

Example vertical NDOS cell

Michel electrons (energy calibration)

Position dependence of cell response (light attenuation, etc.)

Corrected cell response

all vertical cells
NDOS Neutrinos

NuMI neutrino events at NDOS

- Two example distributions: \textit{angle of primary track w.r.t. the neutrino beam, and total visible energy [in photoelectrons]}
- Our Monte Carlo simulation agrees well with observations
The module factory at the University of Minnesota is in full production and have stacks of modules ready to ship.
Far Detector Status

Building Complete!
The first block has been glued together and placement operations are complete!
Watch the progress at http://www.fnal.gov/pub/webcams/nova_webcam/
Far Detector Assembly
Far Detector Assembly
Far Detector Assembly

1st NOvA Block standing in place (Monday, Sept 10)
Near Detector Status

Excavation in progress
Following the accelerator shutdown this spring work has began to upgrade the NuMI beam line to 700kW.

- Turn Recycler from antiproton to proton ring
- Shorten Main Injector cycle from 2.2 seconds to 1.33 seconds
- Overhaul of NuMI target station for 700 kW running

This work is expected to be completed by spring 2013.
Physics Reach

The following sensitivities assume

- $\sin^2 2\theta_{13} = 0.095$
- Optimization for $\sim 4\%$ oscillation probability
- 10% uncertainty on backgrounds
- 41% ($\nu$) and 48% (anti-$\nu$) signal efficiency
Expected exposure

NOvA early reach
Exposure assumptions

mass (kton) vs. time (Jan 2013 to Jan 2016)

mass × P_{beam} (kton MW) vs. time (Jan 2013 to Jan 2016)

P_{beam} (kW) vs. time (Jan 2013 to Jan 2016)

integrated exposure (kton MW yr) vs. time (Jan 2013 to Jan 2016)

(ver: Apr 2012)
Will start with $\nu$ running

- Can switch to $\bar{\nu}_\mu$ any time, optimizing the run plan based on our or others’ results

- $5\sigma$ observation of $\nu_\mu \rightarrow \nu_e$ in first year if NH (even with partial detector and beam commissioning!)
**Example measurement**

**NOvA will measure:**

\[ P(\nu_\mu \rightarrow \nu_e) \text{ at } 2 \text{ GeV} \]

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \text{ at } 2 \text{ GeV} \]

- Starred point is an example NOvA measurement with 1- and 2-sigma contours.
- Depends on CP phase \( \delta \), \( \text{sign}(\Delta m^2) \), and \( \sin^2(2\theta_{23}) \).
- Red and blue ellipses show expected oscillation probabilities for choices of these parameters.
- Simultaneous information on all three parameters.
Mass ordering sensitivity

Significance with which NOvA can establish the mass ordering
Mass ordering sensitivity

Significance with which NOvA can establish the mass ordering (red and blue) and with T2K data (5.5e21 POT) shown in pink and green.
Significance with which NOvA can establish CP violation alone (reb and blue) and with T2K data (5.5e21 POT) shown in pink and green.
The contours are 2D confidence intervals, representing our sensitivity to a joint measurement of $2 \sin^2(\theta_{23})$ and $\delta$.
Conclusion

- NOvA Far Detector construction is underway. First data expected in spring 2013.
- NuMI 700 kW upgrades are also progressing.
- Near Detector excavation has begun.
- NDOS has provided a valuable training ground.
- The large measured value of $\theta_{13}$ puts our mass hierarchy, $\delta_{CP}$, $\theta_{23}$ goals within reach, along with our extended physics program.

Please stay tuned:
http://www-nova.fnal.gov
@NOvANuz on Twitter
https://www.facebook.com/novaexperiment
Example NOνA contours for three test points

\[ \sin^2(2\theta_{23}) = 0.94 \]

4% energy resolution for the QE sample.

Inclusive ν_μ CC sample should be background-free
1 and 2 $\sigma$ Contours for Starred Point

NOvA
Contours 3 yr $\nu$ and 3 yr $\bar{\nu}$
$|\Delta m_{32}^2| = 2.32 \times 10^{-3} \text{ eV}^2$
$\sin^2(2\theta_{13}) = 0.095$
$\sin^2(2\theta_{23}) = 1.00$

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

$\delta = 0$
$\delta = \pi/2$
$\delta = \pi$
$\delta = 3\pi/2$
Expected NO$_{\nu}A$ contours for one example scenario at 3 yr + 3 yr

In “degenerate” cases, hierarchy and $\delta$ information is coupled. $\theta_{23}$ octant information is not.
NOvA measures \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) over an 810 km baseline at a central energy of 2GeV.

\[
P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A - 1)\Delta}{(A - 1^2)}
- \frac{2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23}}{A} \sin A\Delta \frac{\sin (A - 1)\Delta}{A - 1} \sin \Delta
+ \frac{2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23}}{A} \sin A\Delta \frac{\sin (A - 1)\Delta}{A - 1} \cos \Delta
\]

Where: \( \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \), \( \Delta = \Delta m^2_{31} \frac{L}{4E} \), \( A = \frac{(-)}{G_f N_e \frac{L}{\sqrt{2}\Delta}} \)

- The transition probability is dependent on \( \theta_{13}, \theta_{23}, \delta_{CP} \) and \( \Delta m^2_{31} \)
- The reactor measurements do not have the these dependencies
$P(\nu_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.95$

- NOβA
- $|\Delta m_{32}^2| = 2.32 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{13}) = 0.095$
- $\sin^2(2\theta_{23}) = 0.95$

$\Delta m^2 < 0$
- $\delta = 0$
- $\delta = \pi/2$
- $\delta = \pi$
- $\delta = 3\pi/2$

$\Delta m^2 > 0$

$P(\nu_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.97$

- NOβA
- $|\Delta m_{32}^2| = 2.32 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{13}) = 0.095$
- $\sin^2(2\theta_{23}) = 0.97$

$\Delta m^2 < 0$
- $\delta = 0$
- $\delta = \pi/2$
- $\delta = \pi$
- $\delta = 3\pi/2$
Efficiency (from simulation) for detecting a 2 GeV muon passing through a NOvA cell as a function of position along the cell.

- **Design estimates**: $\mu=25$ PE, thr=34 ADC
- **VS5 light level, cold APDs**: $\mu=31.0$ PE, thr=40 ADC
- **VS5+24% light level, cold APDs**
- **VS5+24% light level, warm APDs**
Example NOvA 1σ and 2σ contours, 3+3 yr (ν+ν̅)

\[ \sin^2(2\theta_{13}) = 0.095, \quad \sin^2(2\theta_{23}) = 0.97 \]
MINOS Shaft

NuMI Beamline

NO$_{\nu}$A Near Detector cavern

14.6 mrad off-axis beam

MINOS Hall

Backup
Mean Energy Deposition of Cosmic Ray Muons
P(\bar{\nu}_e) vs. P(\nu_e) in 3 Energy Bins

NO\nu A
\Delta m^2_{23} = 2.32 \times 10^{-3} \text{ eV}^2
\sin^2(2\theta_{13}) = 0.0975
\sin^2(2\theta_{23}) = 1.00
E = 1.69 \text{ GeV}

E = 1.97 \text{ GeV}

E = 2.28 \text{ GeV}

\Delta m^2 < 0

\Delta m^2 > 0

\delta = 0
\delta = \pi/2
\delta = \pi
\delta = 3\pi/2
$P(\bar{\nu}_e) \text{ vs. } P(\nu_e)$ for $\sin^2(2\theta_{23}) = 1$

- NO$\nu$A
- $|\Delta m^2_{32}| = 2.32 \times 10^{-3} \text{ eV}^2$
- $\sin^2(2\theta_{23}) = 1.00$
- $\sin^2(2\theta_{13}) = 0.12$

- $\sin^2(2\theta_{13}) = 0.095$
- $\sin^2(2\theta_{13}) = 0.07$

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

- $\delta = 0$
- $\delta = \pi/2$
- $\delta = \pi$
- $\delta = 3\pi/2$