NOvA Experiment

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For NOvA Collaboration
NOvA Collaboration

140 Collaborators
24 Institutions
4 Countries
NuMI off-axis $\nu_e$ Appearance Experiment

- 810 km long baseline.
- Two detectors 14 mrad off the beam axis.
- Near detector at Fermilab 1 km from target.
- Far detector in Ash River, MN.
- NuMI beam upgraded to 700 kW.

- Search for $\nu_e$ appearance and $\nu_\mu$ survival to measure:
  - $\theta_{13}$
  - Mass hierarchy
  - Constrain CP violation phase
  - $\Theta_{23}$, $\Delta m^2_{32}$
Beam:
- Accelerator shutdown to install upgrades for 700kW beam: March 2012
- Horn1 and target design complete
- Kicker for Booster-Recycler in use
- First recycler injector magnet installed

FD:
- Start construction: Jan 2012
- 1 block ready by start of shutdown
- 50% detector by end of shutdown
- Complete by early 2014

ND:
- Cavern excavation during shutdown
- Prototype in operation at FNAL on the surface
NOvA Detectors Side-by-Side

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

**Near Detector**
- 196 Planes (3m x 4m)
  + 10 Steel/Scint Plane Pairs ("Muon Catcher")
- 220 Ton
- 16000 cells
- Cosmic Ray Muon Rate:
  - ~50 Hz (105 m overburden)
- In-Spill Rate:
  - 10 $\mu$s duration every 1.33 s
  - 30 neutrino events/spill
Detector Technology

- Detectors composed of highly reflective PVC extrusions
- Filled with liquid scintillator (mineral oil + 5% pseudocumene)
- Each cell readout by a wavelength shifting fiber onto one pixel of a 32-pixel avalanche photodiode (APD)
  - 30 PE from far end of cell into APD for MIP
- Num cells: 360000 (Far), 16000 (Near)
NuMI Off-axis Beam

- Enhanced 700 kW NuMI beamline
- Reduce cycle time from 2.2 to 1.3 seconds.
- Increased intensity/cycle with additional Booster batch.
- New horn and target.
- 10μs beam pulse every 1.3 seconds
- 4.9e13 POT/pulse or 6e20 POT/year

- Placing detectors 14 mrad off the beam axis results in 2GeV narrow band beam. Close to the oscillation maximum.
\( \nu_e \) Appearance

- At L/E~400 km/GeV, dominant oscillation mode is \( \nu_\mu \rightarrow \nu_\tau \)
- A few percent of the missing \( \nu_\mu \) could go into \( \nu_e \)

\[
P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{\text{atm}}} e^{-i(\Delta m^2_{32} + \delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2
\]

\[
P_{\text{atm}} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right)
\]

\[
P_{\text{sol}} \approx \cos^2 \theta_{23} \sin^2 \theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E} \right)
\]

'solar' term is less < 1%

- If CP violation phase \( \delta_{CP} \neq 0 \) part of the interference term is asymmetric to \( \nu \leftrightarrow \bar{\nu} \)

\[
P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)
\]

\[
2\sqrt{P_{\text{atm}} P_{\text{sol}}} \left[ \cos \left( \frac{\Delta m^2_{32} L}{4E} \right) \cos \delta_{CP} + \sin \left( \frac{\Delta m^2_{21} L}{4E} \right) \sin \delta_{CP} \right]
\]

Neutrinos(-)

Antineutrinos(+)

J. Nowak (UoFM), PANIC11
$\nu_e$ Appearance with MSW effect

- With 810 km baseline neutrinos will travel through the Earth crust.
- Due to flavor content of the surrounding matter there is an additional term in the Hamiltonian only for $\nu_e$.

\begin{align*}
  a &= \pm \frac{G_F N_e}{\sqrt{2}} \approx (4000 \text{ km})^{-1} \\
  P_{sol} &\approx \cos^2 \theta_{23} \sin^2 2 \theta_{12} \sin^2 (aL) \left( \frac{\Delta m^2_{21}}{4E} \right)^2 \\
  \Delta m^2_{21} &\approx (4000 \text{ km})^{-1}
\end{align*}

Oscillation probability depends on sign of $\Delta m^2$

Oscillation probability modified by about 30% for NOvA

From S. Parke, “Neutrino Oscillation Phenomenology” in Neutrino Oscillations: Present Status and Future Plans
Sensitivity

• Sensitivity to $\sin^2(2\theta_{13}) \neq 0$ after 3 years each of neutrino beam and antineutrino beam in case of normal and inverted hierarchy

• $18\text{e}20$ PoT in each neutrino and antineutrino mode
Comparing to recent results

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

- $L = 310 \text{ km}, 15 \text{ kT}$
- $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$
- $\sin^2(2\theta_{23}) = 1$
- 3 years at 700 kW,
  1.2 MW, and 2.3 MW
for each $\nu$ and $\bar{\nu}$

- $\Delta m^2 > 0$
- $\Delta m^2 < 0$
Resolution of the mass hierarchy

- Resolution of the mass hierarchy after 3 years ($18e20$ PoT) each of neutrino beam and antineutrino beam in case of normal and inverted hierarchy.
- Comparing results from neutrino and antineutrino beams.
Neutrino and antineutrino parameters

• Minos reported $2\sigma$ difference between best fit values for neutrinos and antineutrinos.
• NOvA will be able to test this discrepancy at $3\sigma$ ($5\sigma$) CL after 1(3) year of running in each neutrino and antineutrino mode.

Difference between neutrino and Antineutrino MINOS results.

NULL HIPOTHESIS
NOvA Near Detector Prototype (NDOS)

- Prototype **Near Detector on Surface (NDOS)** – Taking Data Now!
- Identical to future Near Detector
Prototype detector

Main goals are:

- Test detector design and prepare for far detector production.
- Develop DAQ system on custom design hardware
- Tune calibration procedures.

NDOS collects data from NuMI and BNB beams

- Show electron neutrino selection and $e\pi^0$ separation.
- Verify cosmic background suppression.
- Study nuclear hadronization models and multinucleon production.
- Quasi-elastic cross section at 2 GeV.
Lessons Learned

- Redesign of module manifolds to improve its structural integrity
- A few new quality assurance stages in the module production and installation.
- New installation procedures.
- Identification and fixing of DAQ performance issues.
- APDs and electronic redesign.
MC Events in NOvA

**$V_\mu$ 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.

Small shower from 2nd $\gamma$
Neutrinos
Finding Neutrinos

- Neutrino candidates selection cuts bring clear peak of beam events.
- 110 mrad off NuMI axis
- NDOS nearly on Booster axis, but detector rotated wrt axis
Neutrino candidates

- 110 mrad off NuMI axis
- NDOS nearly on Booster axis, but detector rotated wrt axis

<table>
<thead>
<tr>
<th></th>
<th>PoT</th>
<th>NuMI</th>
<th>Cosmic Bg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino</td>
<td>5.6e18</td>
<td>253</td>
<td>39</td>
</tr>
<tr>
<td>Antineutrino</td>
<td>8.4e19</td>
<td>1001</td>
<td>69</td>
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<tr>
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<th>BNB</th>
<th>Cosmic Bg</th>
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</thead>
<tbody>
<tr>
<td>Antineutrino</td>
<td>3e19</td>
<td>222</td>
<td>92</td>
</tr>
</tbody>
</table>
Michel Electrons

- Use Michel electrons for electro-magnetic energy calibration

• q > 300 ADC counts
• t > 40 μsec into the spill
• cluster to be within 30 cm of muon end point

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

- NOvA is on track to make many important contributions to neutrino physics.
  - Measurement of $\theta_{13}$
  - Determination of mass hierarchy
  - More precise measurements of $\Delta m^2$, $\sin^2(2\theta_{23})$
- Far detector construction coming soon.
- NuMI beam upgrade has started.
- Near detector on the surface taking neutrino data now.
BACKUP SLIDES
Calibration

- Cosmic muons provide intra-detector calibration source for every cell
Neutrino Mixing

- Massive neutrinos $\rightarrow$ mass eigenstates $\neq$ weak interaction eigenstate
- Neutrino is produced in flavor $\alpha$ and can be detected in different flavor $\beta$
  - $\rightarrow$ depending on distance ($L$) travelled and neutrino energy ($E$) $\rightarrow L/E$
  - $\rightarrow$ parameters: mixing angles ($\theta_{ij}$) and mass differences $\Delta m^{2}_{ij} = m^{2}_{i} - m^{2}_{j}$

$$P(\nu_{\alpha} \rightarrow \nu_{\beta}) = \left| \sum_{j} U_{\beta j}^{*} e^{-i \frac{m^{2}_{j} L}{2E}} U_{\alpha j} \right|^{2}$$

atmospheric and accelerator
L/E$\sim$500km/GeV

Indications of oscillation
From MINOS and T2K

Reactor + Solar
L/E$\sim$15,000 km/GeV

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & e^{i\delta_{2}} \\ 0 & 0 & e^{i\delta_{3}} \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, $\theta_{ij} = \text{mixing angle}$ and $\Delta m^{2}_{ij} = \text{mass}^{2}$ difference
Comparisons to MC

- Early look at contained events indicates NuMI MC event rate agrees with data

POT normalized

PRELIMINARY

<table>
<thead>
<tr>
<th></th>
<th>NuMI</th>
<th>Cosmic Bg</th>
<th>MC</th>
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</thead>
<tbody>
<tr>
<td>Fiducial</td>
<td>1001</td>
<td>69</td>
<td>861</td>
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<tr>
<td>Fully contained</td>
<td>184</td>
<td>12</td>
<td>187</td>
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Case Study

- Consider $\nu_e$ appearance at the CHOOZ limit:
  - Before cuts, signal is $4\sigma$ above background
  - Cuts on summed event pulse height, event length: $7\sigma$
  - Sophisticated selection based on event topology: $18\sigma$
  - Compare to $\sim 4\sigma$ of MINOS analysis

<table>
<thead>
<tr>
<th>Interaction Type</th>
<th>Events in 3 years</th>
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<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>2500</td>
</tr>
<tr>
<td>NC</td>
<td>2200</td>
</tr>
<tr>
<td>$\nu_e$ CC beam</td>
<td>120</td>
</tr>
<tr>
<td>$\nu_e$ CC signal</td>
<td>270</td>
</tr>
</tbody>
</table>
Sensitivity to Hierarchy

\[
\sin^2(2\theta_{13}) \text{ vs. } P(\bar{\nu}_e) \text{ for } P(\nu_e) = 0.02
\]

L = 810 km, 12 km off-axis

\[\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2\]
\[\sin^2(2\theta_{23}) = 1\]

1 and 2 \(\sigma\) Contours for Starred Point for NOvA

\[\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2\]
\[\sin^2(2\theta_{23}) = 1\]

NOvA 3 years at 700 kW for each \(\nu\) and \(\bar{\nu}\)
Example of Constraining CP

$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$

$\sin^2(2\theta_{23}) = 1$

NO$\nu$A 3 years
at 700 kW
for each $\nu$ and $\bar{\nu}$

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

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

BNB POT vs. Time (for runs with > 1 subrun)
NDOS Energy Spectrum
ND Manifold Architecture

- manifold cover
- fill tube manifold cover
- distributed fill tube
- manifold side seal, left
- manifold center seal
- extrusion assembly
- optical connector
- snout (back)
- snout (front)
- bottom raceway
- bottom fiber tray
- top raceway
- top fiber tray
- fiber cover
- manifold side seal, right
Raceway Functionality

Face of optical connector

- Registers fibers in optical connector
- Guarantees acceptable bend radius
- Shields fibers from events in manifold
- Facilitates assembly

Threading fibers into opt conn
Module Construction Process

2 to 1 gluing

preparation

stringing

threading

flycutting

Inner seal plasma prep