A Program of Long Baseline Neutrino Exploration at Fermilab

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What we know, what we would like to know...

Would like to have more precise knowledge of mixing. Do $\nu_e$'s participate in oscillations at atmospheric scale?

Is $\Delta m^2 > 0$ or $< 0$?

Is CP violated?

The Fermilab long-range plan for long baseline experiments addresses all of these issues in a step-by-step program of detectors and beamline upgrades.
MINOS (Main Injector Neutrino Oscillation Search)

Long baseline oscillation experiment designed to:

- Demonstrate oscillation behavior
  - Confirm and describe flavour oscillations
  - Provide *high statistics* discrimination against alternative models (decoherence, $\nu$ decay, extra dimensions, etc.)
- Precise Measurement of $\Delta m_{23}^2$ to $\sim 10\%$
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations ($\theta_{13}$)
- First direct measurement of $\nu$ vs $\bar{\nu}$ oscillations from atmospheric neutrino events
  - MINOS is the first large deep underground detector with a B-field
The NuMI beam

- 120 GeV protons extracted from the Main Injector in a single turn (8.7ms)
- 1.9 s cycle time i.e. ν beam `on' for 8.7 ms every 1.9 s
- $2.5 \times 10^{13}$ protons/pulse initially
- $2.5 \times 10^{20}$ protons/year initial intensity
- 0.25 MW on target!
- 0.4 MW at $4 \times 10^{13}$ p/pulse!
Tuneable Beam

- Relative position of target and horns allows tuning of beam energy. Act like a pair of highly achromatic lenses.
- MINOS starts with LE beam - best for $\Delta m^2 \sim 0.002 \text{ eV}^2$
- Can run neutrinos or antineutrinos

**LE BEAM:**

$\nu_\mu$ CC Events Observed/yr:
- Low: 1600
- Medium: 4300
- High: 9250

(2.5x10^{20} protons on target/year)
NO
\textbf{νA}

\textbf{NuMI Off-Axis $\nu_e$ Appearance Experiment}

Goals of the NOvA Experiment

- Observe $\nu_e$ appearance
- Sensitivity to $\sin^2(2\theta_{13})$ a factor of 10 below CHOOZ sensitivity, i.e. down to ~ 0.01
- $\sin^2(2\theta_{23})$ measurement to 2% accuracy
- Resolve or contribute to determination of mass hierarchy via matter effects
- Begin to study CP violation in lepton sector
How NOvA Will Meet its Goals

- Reduce backgrounds to $\nu_e$ appearance search by going off the NUMI beam axis for a narrow-band beam. Will use Medium Energy configuration.
- Increase flux/POT at oscillation max by ~2 by going off-axis
- Increase detector mass a factor of 6 over MINOS while reducing cost/kiloton by a factor of 3
- **80% active detector design** (compared to 1.5 $X_0$ sampling in MINOS)
  - electron showers appear as “fuzzy” tracks with 1-4 hits/plane/view
  - allow better separation of $\gamma$’s from $\pi^0$ decays
  - good energy resolution to focus on signal energy region
- Choose long baseline to enhance matter effects
Off-Axis Neutrino Beams
First proposed by BNL E-889

In pion rest frame:

Neutrino and muon energy completely determined by energy conservation

In lab frame:

Neutrino energy depends on boost and angle between neutrino boost direction

\[ E_{\nu} = \frac{0.43 E_{\pi}}{1 + \gamma^2 \Theta^2} \]

At 14 mrad ~all pion decays result in 2 GeV neutrinos

E_{\pi} (GeV) vs E_{\nu} (GeV)
NUMI Neutrino Spectra

- 14 mrad off-axis beam peaks just above oscillation max at ~ 2 GeV with ~20% width
- High energy tail suppressed
  - Reduces NC and τ backgrounds
- Main peak from π decays. K decay ν at much wider angles.
  - Spectrum prediction insensitive to knowledge of k/π ratio
Event Rates

Event rates calculated for

- $L=810$ km, 12 km off-axis
- $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$
- $\sin^2 2\theta_{23} = 1$
- $\sin^2 2\theta_{13} = 0.01$

To Reject Background:

- 50:1 rejection of $\nu_\mu$ CC required $\Rightarrow$ Easy!
- Need 100:1 NC rejection $\Rightarrow$ fine grained, low density
- Good energy resolution $\Rightarrow$ reject beam $\nu_e$
The NOvA Far Detector

- 30 kT, low Z tracking calorimeter
- 80% active material (by weight).
- Optimized for detecting 2 GeV electrons.
- PVC extrusions filled with Liq. Scint.
  - Cell size of 3.87cm x 6.0 cm x 15.7 m
  - 12 extrusions/plane
  - 32 cells/extrusion
  - 1984 planes
  - = 23,808 extrusions
  - = 761,856 channels
- 0.8 mm looped WLS fiber into APD readout

APD Readout
- Cooled to -15°C
- Q.E. 85%
- 22 p.e. at far end
- 250 e noise
- S/N 10:1
Typical NO$_{v}A$ Event:
$\nu_e A \rightarrow p e^- \pi^0, E_\nu = 1.65 \text{ GeV}$

Signal efficiency 24%
signal/background 7.3
signal/sqrt(bg.) 32
NO\nu A Near Detector

- ~ 1 km from NUMI target
- Fits in several existing locations in NUMI access tunnel
  - 3.5 m x 4.8 m x 9.6 m
  - Includes veto, shower containment, muon catcher
- No single location optimizes all parameters
  - Make movable or build more than 1
# NOνA Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date (in months relative to Project Start)</th>
<th>Proposed Calendar Date</th>
<th>FY</th>
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<tbody>
<tr>
<td>Project Start</td>
<td>$t_0$</td>
<td>October, 2006</td>
<td>07</td>
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<tr>
<td>Order extrusions and fiber</td>
<td>$t_0 + 1$</td>
<td>Nov., 2007</td>
<td>07</td>
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<tr>
<td>Start extrusion module factories</td>
<td>$t_0 + 12$</td>
<td>October, 2007</td>
<td>08</td>
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<tr>
<td>Start operation of Near Detector</td>
<td>$t_0 + 21$</td>
<td>July, 2008</td>
<td>08</td>
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<tr>
<td>Far building complete</td>
<td>$t_0 + 31$</td>
<td>May, 2009</td>
<td>09</td>
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<tr>
<td>Start Construction of Far detector</td>
<td>$t_0 + 31$</td>
<td>May, 2009</td>
<td>09</td>
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<tr>
<td>First kiloton operational</td>
<td>$t_0 + 36$</td>
<td>Oct., 2009</td>
<td>10</td>
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<tr>
<td>First 15 kilotons operational</td>
<td>$t_0 + 47$</td>
<td>June 2010</td>
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<td>Full 30 kilotons operational</td>
<td>$t_0 + 57$</td>
<td>July, 2011</td>
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Fermilab Proton Plan

<table>
<thead>
<tr>
<th></th>
<th>Booster Batch Size</th>
<th>Main Injector Load</th>
<th>Cycle Time</th>
<th>MI Intensity</th>
<th>Booster Rate*</th>
<th>Total Proton Rate</th>
<th>Annual Rate at end of Phase</th>
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<tbody>
<tr>
<td></td>
<td>(AP + NuMI) (sec)</td>
<td>(protons) (Hz)</td>
<td>(p/hr) NuMI</td>
<td>BNB</td>
<td></td>
<td></td>
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<td>Actual Operation</td>
<td></td>
<td></td>
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<tr>
<td>July, 04</td>
<td>5.0E+12</td>
<td>1+0</td>
<td>2.0</td>
<td>0.5E+13</td>
<td>5.1</td>
<td>0.8E+17</td>
<td>3.3E+20</td>
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<td>Proton Plan</td>
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<td></td>
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<tr>
<td>Phase I</td>
<td>5.10E+12</td>
<td>2+1→2+5</td>
<td>2.0</td>
<td>3.6E+13</td>
<td>6.3</td>
<td>1.0E+17</td>
<td>2.0E+20 1.5E+20</td>
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<tr>
<td>Phase II</td>
<td>5.3E+12</td>
<td>2+5</td>
<td>2.0</td>
<td>3.7E+13</td>
<td>7.5</td>
<td>1.2E+17</td>
<td>2.2E+20 2.8E+20</td>
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<tr>
<td>Phase III</td>
<td>5.50E+12</td>
<td>2+9</td>
<td>2.2</td>
<td>6.0E+13</td>
<td>8.3</td>
<td>1.5E+17</td>
<td>3.4E+20 2.2E+20</td>
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<td>Beyond Scope of Present Plan</td>
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<tr>
<td>11 Hz</td>
<td>5.50E+12</td>
<td>2+9</td>
<td>2.2</td>
<td>6.1E+13</td>
<td>11.0</td>
<td>2.0E+17</td>
<td>3.4E+20 5.0E+20</td>
</tr>
</tbody>
</table>

TABLE 6: Performance parameters at the completion of each phase of operation.
* Booster rate is limited by radiation levels, except for the 11 Hz case

Fermilab Proton Plan after 2009

Collider operations end in 2009

• Proton bunches in MI used to $\bar{p}$ now available to NuMI $\rightarrow \times 11/9$
• No NuMI downtime due to shot setup (10%) or antiproton transfers to Recycler (5%) $\rightarrow \times 1.176$
• Load 11 booster batches into Recycler and transfer from Recycler to MI in a single booster cycle. MI cycle time reduced from 2.2 s to 1.467 s $\rightarrow \times 1.5$
• $(1.22)(1.176)(1.5)(3.4 \times 10^{20} \text{ p/yr}) = 7.3 \times 10^{20} \text{ p/yr}$

Assume 90% $\rightarrow 6.5 \times 10^{20} \text{ p/yr}$
Statistically Limited

• NO$_{\nu}$A will be statistically limited. Thus, the power of the experiment is proportional to mass times the neutrino flux.

• A Fermilab Proton Driver would provide 25 x 10$^{20}$ pot/yr, a factor of x 4.

• Same effect as building 4 NO$_{\nu}$A's which would cost $500M more and be truly enormous:
Interpreting what we measure

- Experiments measure oscillation probabilities
- Ambiguities in $\sin^2(2\theta_{13})$ due to CP phase $\delta$ and mass hierarchy
- Comparison of NO$\nu$A and T2K at different baselines can break ambiguities
- Possibly use a 2$^d$ NUMI off-axis detector at the 2$^d$ oscillation maximum
- Sensitivity varies with CP phase
- Quote sensitivities vs the fraction of the CP ellipse covered
Sin$^2(2\theta_{13})$ Sensitivity

- Vertical axis is the fraction of possible $\delta$ values for which a $3\sigma$ discovery could be made.
- At large values of $\sin^2(2\theta_{13})$ a $3\sigma$ discovery can be made for all values of $\delta$.
- At lower values of $\sin^2(2\theta_{13})$ a $3\sigma$ discovery is only possible for a range of $\delta$.
- 5% systematic error on background determination included.
There is a reasonable region of parameter space for which NOvA can resolve hierarchy. Proton Driver extends reach by factor of 2.
NOνA alone and with an additional off-axis detector at the 2\textsuperscript{d} maximum

At 2\textsuperscript{d} oscillation maximum
- L=710 km, 30 km off-axis
- Energy lower by x 3
  \[ \Rightarrow \] Matter effect smaller by x 3
  \[ \Rightarrow \] CP violation larger by x 3

Mass hierarchy resolved for all $\delta$ for $\sin^2(2\theta_{13}) > \sim 0.015$

95% C.L. Resolution of Mass Hierarchy

Mass hierarchy resolved for all $\delta$ for $\sin^2(2\theta_{13}) > \sim 0.015$
Sensitivity to CP Violation

- Long baseline experiments generally need to know the hierarchy to measure the CP phase.

- Maximal CPV for one mass ordering can have $\nu$ and $\bar{\nu}$ probabilities corresponding to no CPV for the other mass ordering.

- Neither NOvA nor T2K can demonstrate CP violation in 6 years of running without enhanced proton sources.
Sensitivity to CP Violation (cont.)

- Fraction of possible $\delta$ values for which there is a $3\sigma$ demonstration of CP violation.
  - i.e. $\delta$ is neither 0 nor $\pi$ for both mass orderings.

<table>
<thead>
<tr>
<th>$\Delta m^2 &gt; 0$</th>
<th>$\Delta m^2 &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NOvA</strong></td>
<td><strong>T2K alone</strong></td>
</tr>
<tr>
<td>$75 \times 10^{20}$ pot</td>
<td>$75 \times 10^{20}$ pot</td>
</tr>
<tr>
<td>$\text{4 MW}$</td>
<td>$\text{4 MW}$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$\bar{\nu}$</td>
</tr>
</tbody>
</table>

$3\sigma$ Determination of CP Violation

$L = 810 \text{ km, 12 km off} / \text{T2K + PD + SK}$

$\Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2$

Each $\nu$ and $\bar{\nu}$
Precise Determination of $\sin^2(2\theta_{23})$

- Important because:
  - If mixing is maximal, could be due to unknown symmetry
  - $\nu_{\mu} \rightarrow \nu_e$ oscillation is proportional to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$.
  - If mixing is not maximal, this leads to an ambiguity in comparing reactor and accelerator results.

- Precision measurement requires
  - good statistics
  - excellent $\nu$ energy resolution
  - good control of systematics

- Use totally contained quasi-elastic events
  - Very clean, essentially no NC background
  - Can measure $\sin^2(2\theta_{23})$ to $\sim 1$-$2\%$ level
Precise Determination of $\sin^2(2\theta_{23})$

1$\sigma$ and 2$\sigma$ contours for simultaneous measurement of $\Delta m^2_{32}$ and $\sin^2(2\theta_{23})$ for a 5 year $\nu$ run without a Proton Driver.

5 year $\nu$ run with Proton Driver

For maximal mixing, error on $\sin^2(2\theta_{23})$ is about 0.004 without Proton Driver and 0.002 with a Proton Driver.
Summary

• Fermilab’s long-range plan includes an ongoing program of long baseline neutrino experiments.

• MINOS is the first step in this program and is just now underway  
  (see talk by Mary Bashi at this workshop).

• NO\text{\textsubscript{ν}}A would be the next step
  ▪ Presented current design to Fermilab PAC yesterday
  ▪ Hoping for rapid consideration, by June at the latest
  ▪ NuSAG review by funding agencies to report in June
  ▪ NO\text{\textsubscript{ν}}A and Fermilab are very open to new collaborators

• A Proton Driver is being considered to augment the neutrino program and  
  to support a wide range of other physics programs
  (see talk by John Ellis at this workshop)

• In some scenarios a 2\textsuperscript{d} NUMI off-axis detector at the 2\textsuperscript{d} maximum is helpful