Expected Sensitivities from the $\nu_\mu$ Disappearance Analysis Using the NOvA Detector

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Motivation for Measuring $\theta_{23}$

It tells us the relative proportions of $\nu_\mu$ and $\nu_\tau$ in each of the mass states.

Of the three mixing angles, it is the one currently known to the least precision.

If $\theta_{23}$ is maximal, it may hint at a new symmetry and expose previously unknown underlying structure.

Current Range: $38^\circ < \theta_{23} < 52^\circ$

By combining our $\nu_\mu$ disappearance and our $\nu_e$ appearance measurements of $\theta_{23}$ we can improve the science reach of NOvA.
How NOvA is Sensitive to $\theta_{23}$

Basic disappearance probability:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

With a baseline of $L = 810$ km, and a neutrino energy spectrum peaked at $E = 2$ GeV, NOvA is optimal for $\nu_\mu$ disappearance.

**NOvA Preliminary**
Goals of our $\nu_\mu$ CC Analysis:

1. Deal with the fact that our far detector is on the surface (rejecting cosmic rays.)

2. Use every $\nu_\mu$ CC possible (including uncontained events) by identifying events with well reconstructed muon tracks.

3. Isolate events with high energy resolution (contained $\nu_\mu$ CC quasi-elastic events) to maximize our sensitivity.
Rejection of Cosmic Rays

- We expect roughly 1 cosmic ray per 10 μs beam spill window. At one beam spill per 1.3 seconds, this leads to \( \sim 66,000 \) cosmics per day (in time with the beam).

- With \( \sim 2-3 \nu_\mu \) CC events per day, rejecting 99.999% of the cosmics will still leave us with 1 cosmic per day (we must do better than this...).
By rejecting clusters of hits that occur outside our beam spill window, **we can isolate potential neutrino events.**

For our contained sample, we can apply a series of cuts and a simple cosmic PID, and **reject > 99.9999% of cosmics while maintaining > 95% of our signal events.**

Cosmic rejection for our uncontained events is still under development.
Event Types in NOvA: $\nu_\mu$ CC QE

- QE events are identified by a nice long muon track with at most one other proton-like track.
- The simplicity of these events will provide good energy resolution.
- To improve our sensitivity, we want to try to isolate as many of these as we can.
• Non-QE events are still identified with clear muon track.
• The energy resolution for this sample is lower (due to missing energy from neutral particles) but the statistics will be higher.
Event Types in NOvA: uncontained $\nu_\mu$ CC

- Uncontained events can still be labeled as $\nu_\mu$ CC given an identifiable muon track. We make no attempt to separate the uncontained into QE and non-QE.
- These events will have the lowest energy resolution (due to escaping energy) but they can still contribute to our overall sensitivity.
Background Events: NC

• NC events can be rejected from the $\nu_\mu$ CC analysis due to the absence of a reconstructed muon track.
We use a multivariate analysis based on quantities such as $dE/dx$ and track length for the most muon like track, to generate a $\nu_\mu$ CC PID.

This allows us to separate out NC events from our $\nu_\mu$ CC sample.

Currently, we select events with a PID > 0.725 as $\nu_\mu$ CC events.

- Efficiency = 88.3%
- Purity = 94.3%
- 93.1% of NC events are rejected

Note: $18 \times 10^{20}$ POT $\approx$ 3 years assuming ~65% beam up time.

\[\text{Events} / 18 \times 10^{20} \text{ POT} \]

- CC
- NC

selected

We use a multivariate analysis based on quantities such as $dE/dx$ and track length for the most muon like track, to generate a $\nu_\mu$ CC PID.
In the contained sample, we will distinguish QE from non-QE events in order to improve our sensitivity.

For this we use another multivariate analysis to generate a QE PID for events with one or two tracks based on things such as the amount of energy NOT on the main track and the difference between two different energy estimators.

- For one track events, we select events with a PID > 0.3 as QE.
- Efficiency = 90.5%
- Purity = 82.3%
For the 2 track sample, we use the same PID used for the 1 track samples but we apply a different cut.

For two track events, we select events with a PID > 0.45 as QE.

- Efficiency = 81.3%
- Purity = 50.1%

1 & 2 track samples combined:
- Total QE Efficiency = 87.9%
- Total QE Purity = 70.6%
Energy Spectra by Event Sample

**True Neutrino Energy Spectra:**

- Contained QE Sample
- NOvA preliminary
- 

- Contained non-QE Sample
- NOvA preliminary
- 

- Uncontained Sample
- NOvA preliminary
- 

**Reconstructed Neutrino Energy Spectra:**

- Contained QE Sample
- NOvA preliminary
- 

- Contained non-QE Sample
- NOvA preliminary
- 

- Uncontained Sample
- NOvA preliminary
- 

NOvA Vμ Sensitivities - M.Baird
Combined Sensitivity Example

This plot does not include any systematic errors (we will be limited primarily by our statistics.)
Combined Sensitivity Example

NOvA Preliminary

This plot does not include any systematic errors (we will be limited primarily by our statistics.)

\[ \sin^2 2\theta_{23} = 1.00 \]

3 years $\nu + 3$ years $\bar{\nu}$ 90% CL

- **Red** Contained non-QE CC
- **Blue** Contained QE
- **Black** Combined (includes uncontained events)
• We expect to be able to surpass the current measurement of $\theta_{23}$ after 3+3 years of running.

• If $\sin^2 2\theta_{23} = 1.00$, we expect to surpass the current best measurement after only 1+1 years of running.

• If $\sin^2 2\theta_{23} = 0.95$, we will be able to exclude (at the 90% CL) maximal $\theta_{23}$ after 1+1 years of running.
Conclusions:

• A precision measurement of $\theta_{23}$ is important and NOvA is getting ready to take data for our $\nu_\mu$ disappearance measurements.

• We have a good $\nu_\mu$ CC analysis structure in place including systems for background rejection of NC events and cosmic rays and isolation of $\nu_\mu$ CC QE events for increased sensitivity.

• We anticipate being able to surpass the current measurements for $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$ within a few years!
Special thanks to **UCSC** for hosting DPF 2013!

Your campus is wonderful!
We can detect neutrinos but so far, we can not detect these...
Backups
## Expected Number of Events:

### All neutrino energies:

<table>
<thead>
<tr>
<th>numuCC event type</th>
<th>3 yrs nu-mode sin^2(2*th) = 1.0</th>
<th>3 yrs nu-mode sin^2(2*th) = .95</th>
<th>1 yr nu-mode sin^2(2*th) = 1.0</th>
<th>1 yr nu-mode sin^2(2*th) = .95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cont. QE</td>
<td>93.5</td>
<td>109</td>
<td>31.2</td>
<td>36.3</td>
</tr>
<tr>
<td>Cont. non-QE</td>
<td>435</td>
<td>460</td>
<td>145</td>
<td>153</td>
</tr>
<tr>
<td>Uncontained</td>
<td>937</td>
<td>952</td>
<td>312</td>
<td>317</td>
</tr>
</tbody>
</table>

### Neutrinos with 0 < E < 5 GeV:

<table>
<thead>
<tr>
<th>numuCC event type</th>
<th>3 yrs nu-mode sin^2(2*th) = 1.0</th>
<th>3 yrs nu-mode sin^2(2*th) = .95</th>
<th>1 yr nu-mode sin^2(2*th) = 1.0</th>
<th>1 yr nu-mode sin^2(2*th) = .95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cont. QE</td>
<td>85</td>
<td>101</td>
<td>28.3</td>
<td>33.7</td>
</tr>
<tr>
<td>Cont. non-QE</td>
<td>192</td>
<td>216</td>
<td>64</td>
<td>72</td>
</tr>
<tr>
<td>Uncontained</td>
<td>253</td>
<td>267</td>
<td>84</td>
<td>89</td>
</tr>
</tbody>
</table>

All numbers here are assuming a 700 kW beam and a 14 kTon detector with 65% beam up time.
Basic $\nu_\mu$ CC Analysis:

1. Separate event sample into contained and uncontained events
2. Apply cosmic ray rejection
3. Select $\nu_\mu$ CC events by identifying muon tracks
4. For contained sample, separate out quasi-elastic events to increase sensitivity
5. Perform full three flavor fit with our three samples!

\[\nu_\mu\text{ CC Results!}\]
Current cut is PID > 0.725
# numuCC that pass cut = 496
# NC that pass cut = 30
% NC in numuCC sample = 5.7 %

Current cut is PID > 0.3
# QE that pass cut = 50
# non-QE that pass cut = 10
# NC that pass cut = 0.5

Current cut is PID > 0.45
# QE that pass cut = 17
# non-QE that pass cut = 17
# NC that pass cut = 0.2

% of CC non-QE in QE sample = 28.6 %
% of NC in QE sample = 0.78 %
Basic $\nu_\mu$ CC Cuts:

Cut definitions:

- **Containment (in cm):** $-745 < X < 745 \land -745 < Y < 720 \land 12 < Z < 5950 \land \text{mincell} > 10$
- **Mincell:** the minimum of $\text{cosrej.kalfwdcell}$, $\text{cosrej.kalbakcell}$, $\text{cosrej.cosfwdcell}$, and $\text{cosrej.cosbakcell}$
- **Quality:** number of hits in slice $> 20 \land$ number of continuous planes in slice $> 4 \land \text{cosrej.nhitkal} > 10 \land \text{cosrej.anglebest} > 0.3 \land \text{remid} > 0.725$
- **QE events:** $(\# \text{ of tracks} = 1 \land \text{qepid} > 0.3) \lor (\# \text{ of tracks} = 2 \land \text{qepid} > 0.45)$

numuCC event samples:

- **Contained QE events:** containment $\land$ quality $\land$ QE $\land$ $\text{cosrej.cospid} > 0.2$
- **Contained nonQE events:** containment $\land$ quality $\land$ !QE $\land$ $\text{cosrej.cospid} > 0.2$
- **Uncontained events:** !containment $\land$ quality $\land$ $\text{cosrej.uncontcospid} > 0.9999999$
Major handles for cosmic rejection include:

- Angle of muon w.r.t. beam
- Projected number of cells from muon track start/end, along track direction, to detector edge
- Vertical direction of muon track

These are combined into a cosmic PID for contained cosmic rejection.

After applying some basic quality cuts, for every 1 contained numuCC event, we expect ~3200 cosmic ray events in the beam trigger window. Removal is critical!

<table>
<thead>
<tr>
<th>% remaining after cut</th>
<th>Cosmics</th>
<th>ν MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>precuts</td>
<td>100% (5.5 x 10^6 events)</td>
<td>100% (7.1 x 10^5 events)</td>
</tr>
<tr>
<td>contained</td>
<td>1%</td>
<td>52%</td>
</tr>
<tr>
<td>Cosmic cuts</td>
<td>0% (all removed)</td>
<td>50% (97% of contained)</td>
</tr>
</tbody>
</table>

After cosmic cuts, we expect > 100 neutrinos for every 1 cosmic in the contained sample.
To remove uncontained cosmics, we use the same handles and more:

- muon scattering
- muon vs hadronic energy fraction
- muon track direction from hit timings
- activity near track ends
- plus other variables...

These are combined in a BDT as the uncontained cosmic PID

<table>
<thead>
<tr>
<th>% remaining after cut</th>
<th>Cosmics</th>
<th>$\nu$ MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>precuts</td>
<td>100% ($5.5 \times 10^6$ events)</td>
<td>100% ($7.1 \times 10^5$ events)</td>
</tr>
<tr>
<td>uncontained</td>
<td>99%</td>
<td>48%</td>
</tr>
<tr>
<td>Cosmic cuts</td>
<td>0.007% remaining</td>
<td>43% (90% of uncontained)</td>
</tr>
</tbody>
</table>

After some basic quality cuts, we will have 1 numuCC event for every 80,000 cosmics in the uncontained sample. Even removing 99.99% of cosmics isn’t enough. Still working to improve!
Event Displays with Truth

NOvA Vμ Sensitivities - M. Baird
Event Displays with Truth

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Event Displays with Truth

\[\nu_e (140\text{GeV}) + {}^{12}\text{C} \rightarrow \mu^- (140\text{GeV}) + p (140\text{GeV}) + X_{\text{missing}} \] (QE)

**NOvA - FNAL E929**

Run: 1 / 1
Event: 19 / NuMi
UTC Thu Jan 1, 1970
00:00:0.095000000

NOvA $\nu\mu$ Sensitivities - M.Baird
Rejection of Cosmic Rays

- Applying a clustering algorithm, we can group all of the hits together that belong to the same “source” (i.e. – a cosmic ray or a neutrino event.)
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Perspective on the NOvA Far Detector

Far detector construction is progressing...
Near detector construction has begun!

Instillation of the muon catcher.
\( \nu_\mu \rightarrow \nu_e \) Oscillation Probability

\[
P(\nu_\mu \rightarrow \nu_e) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}} \left[ \cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta) \right]
\]

\[P_{atm} \equiv \sin^2(\Theta_{23})\sin^2(2\Theta_{13}) \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} (\Delta_{31})^2
\]

\[P_{sol} \equiv \cos^2(\Theta_{23})\sin^2(2\Theta_{12}) \frac{\sin^2(\mp aL)}{(\mp aL)^2} (\Delta_{21})^2
\]

- This contains **CP violation**.

- Since the Earth is made of electrons, \( \nu_e \) will be affected in a way that that won’t occur for the \( \nu_\mu \) or the \( \nu_\tau \). This is the **matter effect**. (For \( L = 810 \text{ km} \), \( aL \approx 0.23 \).)

- The dominant term above is proportional to \( \sin^2(\Theta_{23}) \) meaning it is possible to determine if \( \Theta_{23} > 45^\circ \) or \( \Theta_{23} < 45^\circ \) (“resolving the octant.”)
The NOvA Detectors

- 14-kton Far Detector (~3x MINOS).
- 65% active detector.
- 344,064 detector cells read by APDs.
- 0.3 kton Near Detector 18,000 cells/channels.
- Each plane just 0.15 X₀. Great for e⁻ vs π⁰.

Consist of plastic (PVC) extrusions filled with liquid-scintillator, with WLS fibers connected to APDs. Assembled in alternating layers of vertical and horizontal extrusions.
### NOvA Preliminary

**FD**

<table>
<thead>
<tr>
<th>[0,3]GeV</th>
<th>[0,120]GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>63.1</td>
</tr>
<tr>
<td>Nuμ</td>
<td>62.1</td>
</tr>
<tr>
<td>Anti-Nuμ</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**ND**

<table>
<thead>
<tr>
<th>×10^6</th>
<th>[0,3]GeV</th>
<th>[0,120]GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>53.5</td>
<td>93.0</td>
</tr>
<tr>
<td>Nuμ</td>
<td>52.6</td>
<td>89.5</td>
</tr>
<tr>
<td>Anti-Nuμ</td>
<td>0.9</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**[0,3]GeV**: anumu/numu = 1.6%

**[0,3]GeV**: anumu/numu = 1.7%
RHC $\nu_\mu$ CC

FD

NOvA Preliminary

$\nu_\mu$, $\bar{\nu}_\mu$

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-3}</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>10</td>
<td>10^{-1}</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

$\nu_\mu$ CC / 6E20 POT / kTON / 50 MeV

FLUKA08

<table>
<thead>
<tr>
<th>Energy Region</th>
<th>Total</th>
<th>Numu</th>
<th>Anti-Numu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[1,3]$GeV</td>
<td>24.9</td>
<td>2.4</td>
<td>22.5</td>
</tr>
<tr>
<td>$[0,120]$GeV</td>
<td>45.4</td>
<td>13.2</td>
<td>32.2</td>
</tr>
</tbody>
</table>

$[0,3]$GeV: numu/anumu = 10%

ND

NOvA Preliminary

$\nu_\mu$, $\bar{\nu}_\mu$

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-3}</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
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<tr>
<td>10</td>
<td>10^{-1}</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
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$\nu_\mu$ CC / 6E20 POT / kTON / 50 MeV

FLUKA08

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<th>Numu</th>
<th>Anti-Numu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[1,3]$GeV</td>
<td>21.2</td>
<td>2.1</td>
<td>19.1</td>
</tr>
<tr>
<td>$[0,120]$GeV</td>
<td>41.2</td>
<td>11.9</td>
<td>29.3</td>
</tr>
</tbody>
</table>

$[0,3]$GeV: numu/anumu = 10%