Long Baseline Neutrino Experiment Beam Studies

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Outline

Wide-band Long-baseline $\nu$-beam Concept

Optimizing the $\nu$ beam (M. Bishai)

Sensitivities (M. Dierckxsens)
Reminder of the concept

- Potential degeneracies exist between oscillation parameters.
- Parameters assert themselves differently at different energies.
- \( \Rightarrow \) Must cover multiple peaks to disambiguate!

<table>
<thead>
<tr>
<th>Energy:</th>
<th>low</th>
<th>med</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sin^2 2\theta_{13} )</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>( \text{sign}(\Delta m^2_{32}) )</td>
<td>-</td>
<td>-</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>( \delta_{CP} )</td>
<td>✓</td>
<td>✓ ✓</td>
<td>✓</td>
</tr>
<tr>
<td>solar</td>
<td>✓ ✓ ✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>
Beam and Baseline Requirements

- Wide band beam needed to cover features.
- Long baseline to draw features away from Fermi motion dominated energy regime.

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Wide-band Long-baseline $\nu$-beam Concept

Optimizing the $\nu$ beam (M. Bishai)

Sensitivities (M. Dierckxsens)
Beam Optimization (Mary Bishai)

The best beam:

- Cover the energy of interest: from Fermi motion limit to high enough to resolve matter effect.
  - target design, focusing, beam energy and decay pipe geometry.
- Avoid unneeded high energy flux; source of low energy neutral current events that mimic $\nu_e$ charged current interactions.
  - beam energy, beam plug(?), (slightly) off-axis beam.

DUSEL 120 GeV, NuMI horns 250kA, beam plug, 280m tunnel. NC background
Using a simplified WCe detector response we can approximate the signal rates and NC backgrounds in various bins. Thus we can compare the different beam options:

**νe Appearance Rates, various DUSEL beam options**

- **Total 0.5-6 GeV**
- **0.5-1.5 GeV (x10)**
- **1.5-3.0 GeV**
- **3.0-6.0 GeV**

**DUSEL Beam Options Signal/sqrt(Background)**

- **Total 0.5-6 GeV**
- **0.5-1.5 GeV (x10)**
- **1.5-3.0 GeV**
- **3.0-6.0 GeV**

Best with NuMI horn design:

- **Appearance rate**: 120 GeV and 350 kA horn current
- **Sig/√Bkg**: 60 GeV and 250 kA horn current
Optimization Summary

- Factor of 2 variation in flux.
- Mostly on the high energy side
- Degrades $\text{Sig}/\sqrt{\text{Bkg}}$ for $\nu_e$ appearance.
- Now considering 3 horn design
  - $\Rightarrow \sim 40\%$ increase in 1 GeV.
Wide-band Long-baseline $\nu$-beam Concept

Optimizing the $\nu$ beam (M. Bishai)

Sensitivities (M. Dierckxsens)
Consider Full/Limited Detectors at Homestake Mine

100/300kT Water Cherenkov

Scale known Super-Kamiokande. (well understood tech)

Assume high efficiency/purity, no NC bkg. (much R&D needed)
Beam and Detector Assumptions

Beam assumptions
- 120 GeV, NuMI horns, with beamplug
- 1 MW proton beam power
- Running time: 6 years = 3 $\nu + 3 \bar{\nu}$
- Assume $1.9 \times 10^7$ sec/year $\Rightarrow 10^{21}$ protons/year
- (Future work: 0.7 $\rightarrow$ 2MW, no beamplug, 3 horns)

Detector assumptions:
- 100kT and 300kT Water Cherenkov
  - Scale atm-$\nu$ MC from SK, not optimized for large detector.$^1$
  - Single-ring events only (improvements still to be found)
- 15kT and 50kT Liquid Argon, high efficiency/purity.
  - Assumptions: 80% CC$_{\nu_e}$ eff., 0% background, $\sigma_E = 5%/\sqrt{E}$

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$^1$C. Yanagisawa
Sensitivities and Measurements (Mark Dierckxsens)

Look at sensitivities to:
- $\sin^2 2\theta_{13} \neq 0$
- Mass hierarchy
- CP violation

And measurements of:
- $\theta_{13}, \delta_{CP}$

Calculations done with GLoBES (P. Huber, et al.). Application and analysis by Mark Dierckxsens.
Limit on $\theta_{13}$ – Full Size Detector

$3\sigma_{\text{worse}} = 8 \times 10^{-3}$

$3\sigma_{\text{worse}} = 7 \times 10^{-3}$
Limit on $\theta_{13}$ – Limited Detector

100kTon WC

$\nu + \bar{\nu}$, 100 kt WCC
$30 + 30 \times 10^{20}$ PoT

$3\sigma$ ($\Delta m^2_{31} > 0$)
$5\sigma$ ($\Delta m^2_{31} < 0$)

$3\sigma_{\text{worse}} = 1.5 \times 10^{-2}$

15kTon LAr

$\nu + \bar{\nu}$, 15 kt LAr
$30 + 30 \times 10^{20}$ PoT

$3\sigma$ ($\Delta m^2_{31} > 0$)
$5\sigma$ ($\Delta m^2_{31} < 0$)

$3\sigma_{\text{worse}} = 1.3 \times 10^{-2}$
Mass Hierarchy – Full Size Detector

300kTon WC

\[ \nu + \bar{\nu}, 300 \text{ kt WCh} \]
\[ 30+30 \times 10^{20} \text{ PoT} \]
- \[3\sigma (\Delta m^2 > 0)\]
- \[5\sigma (\Delta m^2 > 0)\]
- \[3\sigma (\Delta m^2 < 0)\]
- \[5\sigma (\Delta m^2 < 0)\]

\[3\sigma_{\text{worse}} = 8 \times 10^{-3}\]

50kTon LAr

\[ \nu + \bar{\nu}, 50 \text{ kt LAr} \]
\[ 30+30 \times 10^{20} \text{ PoT} \]
- \[3\sigma (\Delta m^2 > 0)\]
- \[5\sigma (\Delta m^2 > 0)\]
- \[3\sigma (\Delta m^2 < 0)\]
- \[5\sigma (\Delta m^2 < 0)\]

\[3\sigma_{\text{worse}} = 7 \times 10^{-3}\]
Mass Hierarchy – Limited Detector

100kTon WC

\(\nu^+\bar{\nu}, 100 \text{ kt WCC}\)

\(30+30 \times 10^{20} \text{ PoT}\)

- \(3\sigma (\Delta m_{31}^2 > 0)\)
- \(5\sigma (\Delta m_{31}^2 > 0)\)
- \(3\sigma (\Delta m_{31}^2 < 0)\)
- \(5\sigma (\Delta m_{31}^2 < 0)\)

\[3\sigma_{\text{worse}} = 1.5 \times 10^{-2}\]

15kTon LAr

\(\nu^+\bar{\nu}, 15 \text{ kt LAr}\)

\(30+30 \times 10^{20} \text{ PoT}\)

- \(3\sigma (\Delta m_{31}^2 > 0)\)
- \(5\sigma (\Delta m_{31}^2 > 0)\)
- \(3\sigma (\Delta m_{31}^2 < 0)\)
- \(5\sigma (\Delta m_{31}^2 < 0)\)

\[3\sigma_{\text{worse}} = 1.3 \times 10^{-2}\]
CP Violation – Full Size Detector

Sensitivities (M. Dierckxsens)

300kTon WC

\[ \sin^2 2\theta_{13} = 0.019 \]

50kTon LAr

\[ \sin^2 2\theta_{13} = 0.015 \]
CP Violation – Full/Limited Detector – Water Cherenkov

300kTon WC

$v + \bar{v}, 300$ kt WCh
$30+30 \times 10^{20}$ PoT

- $3\sigma$ ($\Delta m_{31}^2 > 0$)
- $5\sigma$ ($\Delta m_{31}^2 < 0$)

$3\sigma, 50\% \delta_{CP} : \sin^2 2\theta_{13} = 0.019$

100kTon WC

$v + \bar{v}, 100$ kT WCh
$30+30 \times 10^{20}$ PoT

- $3\sigma$ ($\Delta m_{31}^2 > 0$)
- $5\sigma$ ($\Delta m_{31}^2 < 0$)

$3\sigma, 50\% \delta_{CP} : \sin^2 2\theta_{13} \sim 0.1$
$\theta_{13}, \delta_{cp} – \text{Full Size Detector}$

300kTon WC

50kTon LAr

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$\theta_{13}, \delta_{cp} - \text{Limited Detector}$

100kTon WC

15kTon LAr

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Summary of full vs. limited detector

Water Cherenkov 300 → 100 kTon.

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>Limited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity to $\sin^2 2\theta_{13}$ (worse case)</td>
<td>0.008</td>
<td>0.015</td>
</tr>
<tr>
<td>$3\sigma$ mass hierarchy ($\sin^2 2\theta_{13}$)</td>
<td>0.008</td>
<td>0.015</td>
</tr>
<tr>
<td>($\theta_{13}, \delta_{cp}$)</td>
<td>($\pm 10%, \pm 20^\circ$)</td>
<td>($20%, \pm 40^\circ$)</td>
</tr>
</tbody>
</table>

⇒ limited detector does $\sim \times 2$ worse than full scale design.
Summary

- To resolve neutrino oscillation parameter degeneracies in a single experiment one needs a powerful ($\sim 1$MW) proton beam producing a wide band neutrino beam, sent a long distance ($>1000$km) to a large (100s kTon H$_2$O / 10s kTon LAr) detector.
- Optimizations of the beam to maximize the flux in the required region are underway with more phase space still to explore. Increasing low energy will likely need 3 horns.
- Performance of 300 kTon Water Cerenkov and 50 kTon LAr far detectors are comparable, given the assumptions (unoptimized WC, near-perfect LAr)
- Reducing scope to 100 kTon WC / 15 kTon LAr significantly degrades performance, or requires 6 → 18 years of running to remain comparable.
Thanks.