(Physics Potential of) a Very Long Baseline Neutrino Experiment using a Wide Band Beam

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Outline

✔ Motivation for and concept of a very long baseline (VLBL) neutrino oscillation experiment
✔ Possibility of neutrino beams in the US
✔ Possibility of deep underground water Cherenkov detector in the US
✔ Recent improvements in $e/\pi^0$ separation in a water Cherenkov detector
✔ Physics potential: see talk D. Marfatia
Very Long Baseline Experiment

- Introduction
- Concept
- $\nu_\mu$ disappearance
- $\nu_e$ appearance
**Three neutrino oscillations**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

**PMNS matrix:**
- 3 mixing angles
- 1 CP phase
- (2 CP Majorana phases)

**solar**

\[
U = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[\theta_{12} \approx 34^\circ\]

**atmospheric**

\[
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\]

\[\theta_{23} \approx 45^\circ\]

\[\sin^2 2\theta_{13} < 0.11 \ (90\% CL)\]

\[\delta = ???\]

Neutrino masses must differ to observe \(\nu\) oscillations:

\[\Delta m_{21}^2 = m_2^2 - m_1^2 \approx +7.9 \times 10^{-5} \text{ eV}^2\]

\[|\Delta m_{32}^2| = |m_3^2 - m_2^2| \approx 2.6 \times 10^{-3} \text{ eV}^2\]

\[\Delta m_{31}^2 = \Delta m_{21}^2 + \Delta m_{31}^2\]

\[\Delta m_{32}^2 > 0\]

\[\Delta m_{32}^2 < 0\]
VLBL Concept

Very long baseline (VLBL) concept:
- Long distances between production and detection
- Wide band $\nu_\mu$ beam
- Higher neutrino energies ($>0.5$ GeV)

A single VLBL experiment will have:
- increased sensitivity to $\sin^22\theta_{13}$
- good sensitivity to $\delta_{CP}$
- potential for resolving mass hierarchy (sign of $\Delta m^2_{32}$)
- capability for precision measurements of $\Delta m^2_{32}$ & $\sin^22\theta_{23}$
\( \nu_\mu \) disappearance

Observe multiple nodes in oscillation pattern:
- ✔ less dependent on flux normalization

Longer distances \( \rightarrow \) nodes at higher energies:
- ✔ easier to reconstruct
- ✔ higher cross sections

Baseline \( >1000\text{km} \):
- ✔ 2 nodes out of fermi motion domain

Precision measurement \( \Delta m_{32}^2 \) and \( \sin^2 2\theta_{23} \)

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left( \frac{1.27 L \Delta m_{32}^2}{E} \right)
\]
\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((\hat{A} - 1)\Delta)}{(\hat{A} - 1)^2} \]

\[ + \alpha J_{CP} \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)}{\hat{A}(1 - \hat{A})} \]

\[ + \alpha I_{CP} \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)}{\hat{A}(1 - \hat{A})} \]

\[ + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \]

"atmospheric"

"CP effects"

"solar"

\[ \alpha = \Delta m^2_{21} / \Delta m^2_{31} \approx 0.03, \quad \Delta = \Delta m^2_{31} L / 4 E \]

\[ \hat{A} = 2VE / \Delta m^2_{31} \approx (E_\nu / GeV) / 11 \quad (\text{Earth's crust}), \quad V = \sqrt{2} G_F n_e \]

\[ J_{CP} = \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}, \]

\[ I_{CP} = \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \]

Numerical calculations used for actual results
$\nu_e$ appearance

✓ $P(\nu_\mu \rightarrow \nu_e)$ depends on all oscillation parameters and has following degeneracies:
  - intrinsic $(\theta_{13}^{}, \delta_{\text{CP}}^{}) \leftrightarrow (\theta_{13}'^{}, \delta_{\text{CP}}')$
  - sign $\Delta m_{32}^2 \leftrightarrow -\Delta m_{32}^2$
  - octant $\theta_{23}^{} \leftrightarrow \pi/2 - \theta_{23}^{}$

✓ atmospheric term has effect of $\sin^2 \theta_{13}^{}$ and matter effects ($\sim L$)

✓ CP violating term $\sim L/E$, flux $\sim L^{-2}$
  → sensitivity to $\delta_{\text{CP}}^{}$ independent of distance
  (Marciano hep-ph/0108181)

✓ solar term dominated by $\Delta m_{21}^2$ and grows as $\sim (L/E)^2$
$\nu_e$ appearance

Sensitive to different parameters in different energy regions:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>sign($\Delta m^2_{32}$)</td>
<td>0</td>
<td>0</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>

Fully exploit shape of appearance spectrum:
helps in resolving ambiguities with one experiment at one baseline
Baselines in US

The U.S. DUSEL sites enjoy a natural geographical advantage not present in other potential world sites.

Sensitivity studies will cover 500-3000km baselines!
Wide band neutrino beams

✓ Making conventional $\nu_\mu$ beams
✓ Beam from BNL
✓ Beam from FNAL
✓ Flux calculations
Making $\nu_\mu$ beams

NuMI example:

- shoot protons on target
- magnetic horns: focus pions to get more flux and select $\nu$ or anti-$\nu$
- decay pipe for pions to decay
- material to absorb remaining hadrons and muons
Beam from BNL

AGS upgrade: 28 GeV 1MW neutrino beam
✓ Increase intensity and repetition rate
✓ Needs new power supply, RF and replacing booster with 1.2 GeV SC linac

neutrino beamline on a hill:
✓ keep radiation above water table
✓ 45m high
✓ target on top
✓ 200 m decay pipe
✓ pointing ~11° down

Total cost estimate: $273M (excl. contingency)

Possible proton beam power upgrades:

a) Proton plan:
   ✓ More protons in MI
   ✓ After Tevatron: batches pbar production available

b) Super NuMI: after Tevatron
   ✓ Phase I: use Recycler as pre-injector
   ✓ Phase II: also use Accumulator

c) High Intensity Neutrino Source (a.k.a. Proton driver):
   ✓ Replace booster with 8GeV sc linac

Phase II of sNuMI is part of the plan for the NOVA-I

“Fermilab Proton Projections for Long-Baseline Neutrino Beams”
Bob Zwaska, FNAL-BEAM-DOCS-2393
Beam from FNAL

Flexibility of proton energy:

![Graph showing the flexibility of proton energy with different peak beam powers for various proton energies.](image)
Beam from FNAL

Beamline: use existing NuMI extraction

✔ target hall: 45m
✔ decay pipe: 400m
✔ near detector: 300m from end decay pipe

Angles to:
✗ Homestake: 5.8°
✗ Henderson: 6.7°
Flux Calculations

Simulation using NuMI Monte Carlo (gnumi):

✓ based on GEANT3 and Fluka05
✓ validated by MINOS Near Detector data

Modifications:
✓ Target
✓ Horns
✓ Decay pipe: r=2m, l=380m

→ Wide Band Low Energy (WBLE) beam

Flux Calculations

- Good agreement BNL & WBLE calculations (28GeV)
- Increase flux: longer decay pipe & higher proton energy
Water Cherenkov Detector

✓ Requirements
✓ UNO at Henderson
✓ Modular detector at Homestake
✓ e/π^0 separation
Water Cherenkov detector

- well established technique
- scale few times Super-K 50kT (22.5kT fiducial)
- several 100kTs (depends on physics)
- 20%-40% PMT coverage (depends on physics)
- 10% energy resolution on quasi-elastic $\nu_e$ interactions
- rejection neutral current interactions x10-20
- underground to reduce cosmics (no veto counter needed if deep enough)
Detector at Henderson

UNO detector:
- 1 large cavern
- 3 optically separated modules of 60x60x60 m³
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse cost estimate scaling Super-K: $500M
Detector at Henderson

Modular detector:
- module: ~50m Ø, ~50m h
- 100kT fiducial
- depth 4850 mwe
- coverage 25%
- 12 inch PMT

- initial detector 3 modules
- expand to 10 modules (or more) to get Mt detector
- detailed cost estimate: $100M/module

“Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory", M. Diwan et al., hep-ex/0608023
Water Cherenkov Simulation

- Full GEANT simulation of Super-KamiokaNDE used
- 40% PMT coverage
- Atmospheric neutrino MC reweighted to match expected flux 28GeV AGS beam

“Pattern of Light” fit improves standard Super-K $\pi^0$ finder

Improvements at lower opening angles with finer granularity expected

“Background Rejection Study in a water Cherenkov detector”, C. Yanagisawa, C. K. Jung, P.T. Le, B. Viren, July 18, 2006
Water Cherenkov Simulation

- Select single ring events and electrons
- Analysis of single ring pattern

- No Δ log-likelihood cut (100% signal retained after initial cuts)

TRADITIONAL ANALYSIS
(ε~80-90% for QE)

Preliminary
Signal + backgrounds
Background from π⁰
CP+45°
ν_e background

Signal

Δ log-likelihood cut (~50% signal retained)

1300km
440kT

Preliminary
Signal: ν_e CC
Bkgd: all NC, beam ν_e

CP+45°

likelihood cut keeping 50% signal: S/B: 700/2004 → 350/169

confirmed using T2K MC

“T2KK Project and Likelihood study”, Fanny Dufour, U.S. Long Baseline Neutrino Experiment Study Workshop, September 16-17, 2006
$\nu_e$ appearance spectrum

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>$\nu_e$ appearance rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td></td>
</tr>
</tbody>
</table>

$2500kT^*MW^*(10^7)s$, 1300km, 28GeV

$\Delta m^2_{(21,31)} = 8e-5, 2.5e-3 \text{ eV}^2$

$\sin^2 2\theta_{(12,23,13)} = 0.86, 1, 0.04$

Signal + bg:

- $\delta_{CP} = 0$ (1292 events)
- $135^0$ (1675 events)
- $45^0$ (1069 events)

bg:

(513 events)

1300km $\nu_e$ appearance rates

5000kT*MW*(10^7)s, 1300km, 28GeV

$\Delta m^2_{(21,31)} = 8e-5, 2.5e-3 \text{ eV}^2$

$\sin^2 2\theta_{(12,23,13)} = 0.86, 1, 0.04$

Signal + bg:

- $\delta_{CP} = 0$ (1147 events)
- $-135^0$ (902 events)
- $45^0$ (1266 events)

bg:

(532 events)

Signal (CP=0) 1292 anti-$\nu$ 1147

Background 513 S/B 2.5

532 2.2
\( \sin^2 2\theta_{13} \) sensitivity

\( \nu + \text{anti-\( \nu \) on 1300 km} \)

- Discovery potential for \( \sin^2 2\theta_{13} \neq 0 \)
- Not strongly dependent on \( \delta_{CP} \)
- \( 3\sigma \) discovery potential for \( \sin^2 2\theta_{13} > 0.005 \)
- See next talk for more details on sensitivity calculations
Conclusions

✔ Reviewed concept and motivation for a very long baseline experiment using a wide band beam.

✔ MW scale proton machine possible at FNAL & BNL. Wide band beam simulated using experimentally validated numi MC.

✔ Large, deep underground water Cherenkov detectors are considered at Homestake and Henderson mines. Detailed cost estimate for a modular detector at Homestake.

✔ Recent work on $e/\pi^0$ separation shows required level of background reduction is feasible.

✔ Next talk: details sensitivity to oscillation parameters

✔ Sending a wide band $\nu_\mu$ beam towards a large underground water Cherenkov detector seems feasible with known technologies!
Backup Slides
### Proton Math (120 GeV):

<table>
<thead>
<tr>
<th>Protons</th>
<th>Cycle Time</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$25 \times 10^{12}$</td>
<td>2.4 s</td>
<td>200 kW</td>
</tr>
<tr>
<td>$30 \times 10^{12}$</td>
<td>2 s</td>
<td>280 kW</td>
</tr>
<tr>
<td>$25 \times 10^{12}$</td>
<td>2.4 s</td>
<td>200 kW</td>
</tr>
<tr>
<td>$30 \times 10^{12}$</td>
<td>2 s</td>
<td>280 kW</td>
</tr>
<tr>
<td>$37 \times 10^{12}$</td>
<td>2.2 s</td>
<td>320 kW</td>
</tr>
<tr>
<td>$49 \times 10^{12}$</td>
<td>2.2 s</td>
<td>430 kW</td>
</tr>
<tr>
<td>$37 \times 10^{12}$</td>
<td>2.2 s</td>
<td>320 kW</td>
</tr>
<tr>
<td>$49 \times 10^{12}$</td>
<td>2.2 s</td>
<td>430 kW</td>
</tr>
<tr>
<td>$49 \times 10^{12}$</td>
<td>1.33 s</td>
<td>700 kW</td>
</tr>
<tr>
<td>$83 \times 10^{12}$</td>
<td>1.33 s</td>
<td>1200 kW</td>
</tr>
<tr>
<td>$150 \times 10^{12}$</td>
<td>1.33 s</td>
<td>2200 kW</td>
</tr>
</tbody>
</table>

- **Current complex**
  - No Improvements
- **Proton Plan**
  - Increase Beam Intensity
- **SNuMI – Recycler**
  - Reduce Cycle Time
- **SNuMI – Accumulator**
  - Increase Beam Intensity
- **HINS**
  - Increase Beam Intensity
MI ramp rates
ABS vs WBLE flux

Good agreement between original AGS beam and WBLE predictions
### TABLE I: Target and beam parameters: NuMI and WBLE

<table>
<thead>
<tr>
<th>Component</th>
<th>NuMI</th>
<th>WBLE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape:</td>
<td>47 rectangular segments</td>
<td>solid cylindrical rod</td>
</tr>
<tr>
<td></td>
<td>each 6.4mm wide × 18mm high</td>
<td>12mm diameter</td>
</tr>
<tr>
<td></td>
<td>and 20mm long</td>
<td>0.8 m total length</td>
</tr>
<tr>
<td></td>
<td>= 0.954 m total length</td>
<td></td>
</tr>
<tr>
<td>Material:</td>
<td>graphite</td>
<td>carbon-carbon composite</td>
</tr>
<tr>
<td>Density:</td>
<td>1.784 g/cm³</td>
<td>2.1 g/cm³</td>
</tr>
<tr>
<td>Cooling:</td>
<td>water cooling tubes</td>
<td>Helium flow cooled</td>
</tr>
<tr>
<td><strong>Proton beam parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy:</td>
<td>120 GeV</td>
<td>28, 40, 60, 120 GeV</td>
</tr>
<tr>
<td>RMS width:</td>
<td>$\sigma_x = 1.1\text{mm}, \sigma_y = 1.25\text{mm}$</td>
<td>$\sigma_x = 1.5\text{mm}, \sigma_y = 1.5\text{mm}$</td>
</tr>
</tbody>
</table>
Modular detector: cost and time

Construction costs for 3 caverns:

Table 3: Comparison of single chamber versus three chamber cost

<table>
<thead>
<tr>
<th>Estimated Costs ($MM)</th>
<th># Of Chambers</th>
<th>1</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor &amp; Benefits</td>
<td></td>
<td>$5.51</td>
<td>$10.94</td>
</tr>
<tr>
<td>Mining and Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Operation</td>
<td></td>
<td>$1.30</td>
<td>$8.89</td>
</tr>
<tr>
<td>Supplies</td>
<td></td>
<td>$4.51</td>
<td>$13.35</td>
</tr>
<tr>
<td>Precast Concrete Liner</td>
<td></td>
<td>$3.25</td>
<td>$9.75</td>
</tr>
<tr>
<td>Other (Outside Contractors)</td>
<td></td>
<td>$0.17</td>
<td>$0.52</td>
</tr>
<tr>
<td>30% Contingency</td>
<td></td>
<td>$4.40</td>
<td>$11.48</td>
</tr>
<tr>
<td>TOTAL(2002)</td>
<td></td>
<td>$19.1</td>
<td>$49.93</td>
</tr>
<tr>
<td>TOTAL(2007)</td>
<td></td>
<td>$29.1</td>
<td>$66.1</td>
</tr>
</tbody>
</table>

Costs of 3 detector modules:

<table>
<thead>
<tr>
<th>Cost Description</th>
<th>Amount</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>$3M</td>
<td>Extrapolated from SNO</td>
</tr>
<tr>
<td>Procurement/Module</td>
<td>$5M</td>
<td>Water purification, distribution, calibration</td>
</tr>
<tr>
<td>Production/Module</td>
<td>$62.1M</td>
<td>For 25% PMT coverage of 11,000 m²</td>
</tr>
<tr>
<td>Total (3 Modules)</td>
<td>$242.7M</td>
<td>Includes 25% contingency</td>
</tr>
</tbody>
</table>

Action Dates

- Detector Strategic Plan
- Homestake DUSEL Proposal
- Phase-1 Detector CDR Review
- Phase-1 Detector TDR Review
- Phase-1 Detector Const. Start
- Phase-1 Detector Operational
- Phase-2 Detector CDR

CY06 07 08 09 10 11 12 13 14
Detector-1 Conceptual Design
Detector-1 Technical Design
Detector-1 Construction
Detector-2 Conceptual Design
Detector-2 Technical Design
Detector-2 Construction
Comparison with Chiaki's efficiency

“T2KK Project and Likelihood study”, Fanny Dufour, U.S. Long Baseline Neutrino Experiment Study Workshop, September 16-17, 2006

NB: background contains only NC.

Good agreement at low energy