BROOKHAVEN NATIONAL LABORATORY

BNL-79544-2007-CP

Sensitivities of Future Long Baseline Experiments in the U.S.

Mark Dierckxsens
The Enrico Fermi Institute, the University of Chicago, Chicago, Illinois, 60637

Presented at the 9th^h International Workshop on Neutrino Factories, Superbeams and Betabeams.
Okayama University, Okayama, Japan
August 6 – 11, 2007

November, 2007

Physics Department
Electronic Detector Group
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed on recycled paper

Sensitivities of Future Long Baseline Experiments in the U.S.

Mark Dierckxsens

The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois, 60637

Abstract.
Sensitivities to neutrino oscillation parameters for possible very long baseline neutrino oscillation experiments are discussed. The reach for observing a non-zero mixing angle θ_{13}, establishing CP violation and determining the mass hierarchy are compared between various experimental options. Different possibilities for neutrino beams are briefly described, as well as the assumptions about the performance of a large water Cherenkov and liquid Argon detector.

Keywords: Neutrino Oscillations
PACS: 01.30.Cc,14.60Pq

INTRODUCTION

Observation of a non-zero value for θ_{13} opens the door for a measurement of CP violation in the lepton sector and the determination of the neutrino mass hierarchy. Several experiments are expected to reveal more information on this angle in near future reactor [1, 2] and mid term accelerator [3, 4] experiments. An extensive program is required to study neutrino oscillations beyond the scope of these experiments.

A joint study between Brookhaven National Lab (BNL) and Fermi National Accelerator Lab (FNAL) was organized to investigate the potential of a very long baseline experiment in the United States. The conclusions of this elaborate effort are discussed in [5], wherein references to supporting documentation can be found (see also [6]).

Most calculations were performed using the GLoBES [7] software package. The basis for the inputs will be described in the next sections, after which the results will be discussed.

NEUTRINO BEAMS AND BASELINES

One possibility is to use the existing NuMI beamline and place a detector at 810km about 0.8° off-axis. Simulations of the expected spectra are base upon GNuMI which is well tested against experimental data [8].

The same Monte Carlo is used simulate the Wide Band Low Energy (WBLE) beam with a few modifications: a new design for the horns and a 400m long, 4m diameter decay pipe. Incident proton energies of 120 GeV were preferred over lower energy beams due to a higher total neutrino yield. The beam has been tilted slightly off-axis by 0.5° to maintain a large fraction of the low energy flux but to suppress the high energy tail. Results quoted use this configuration, although calculations were also performed for other options in this study.

The default assumes a total of 6×10^{21} protons-on-target (PoT) are delivered to produce above mentioned beams, divided equally among the neutrino and anti-neutrino running mode.

Various baseline lengths were considered for the WBLE beam but only results for 1300km will be shown. This is the distance from FNAL to the Homestake mine, which recently was singled out as the candidate for a Deep Underground Science and Engineering Laboratory.

NEUTRINO DETECTORS

A comparison is made between two detector technologies: the well established water Cherenkov (WCh) technique on the one hand, and a Liquid Argon (LAr) detector on the other hand. The parametrization of the detector responses used as input for the sensitivity calculations are described in this section.

Water Cherenkov Detector

The detector performance is based on the elaborate work performed to reduce the contamination from NC interactions in the ν_e selection procedure using SuperK Monte Carlo events [9]. Quantities obtained from a significantly improved π^0 finding algorithm are combined with other variables in a likelihood based selection method. This increases the signal-to-background ratio drastically in addition to the standard SuperK cuts to select single ring electron-like events inside the fiducial volume. The efficiencies used for the calculations reported here are matched to these results. An independent group confirmed these findings using similar techniques [10].

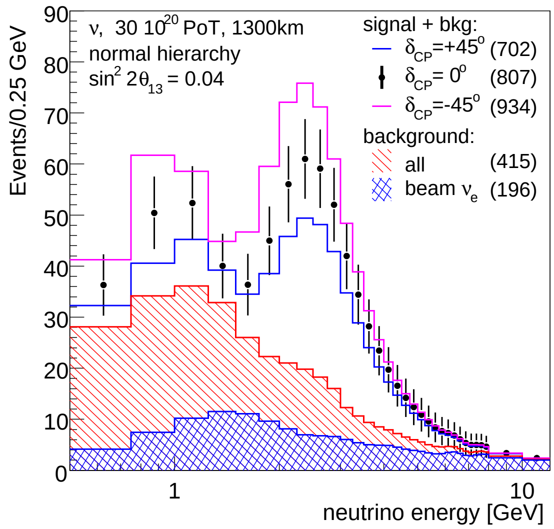

FIGURE 1. The expected ν_e appearance spectrum for a 300 kton WCh detector for $\sin^2 2\theta_{13} = 0.04$ exposed to 3×10^{21} PoT producing a neutrino beam. The points assume $\delta_{cp} = 0°$ and normal mass hierarchy, while the solid lines have different δ_{cp} values. The different background contaminations are indicated by the hatched histograms. Total event rates for each variation are given between brackets.

The energy smearing function for ν_e signal events is based on a GEANT3 [11] simulation of quasi-elastic interactions and is about $10\%/\sqrt{E}$ at 1 GeV. It is in very good agreement with the results from the two studies mentioned above, except for missing asymmetric tails due to non-quasi elastic events. However, this is shown to have a small effect on the final result [10]. The resolution functions for NC interactions are based on the NUANCE Monte Carlo program [12].

Figure 1 shows the expected spectrum using a 300 kton fiducial volume water Cherenkov detector.

Liquid Argon Detector

A Liquid Argon detector is often considered as the best possible neutrino detector due to a fully active calorimetric medium with fine grained tracking capabilities. This should allow for a high signal selection efficiency while practically eliminating all neutral current backgrounds.

Based on a hand scanning study [13], the selection efficiency for charged current ν_e interactions is taken as 80% with a complete rejection of NC background events. The energy resolution for quasi-elastic events is assumed to be $5\%/\sqrt{E}$, while this is $20\%/\sqrt{E}$ for all other type of interactions.

The fiducial mass of the LAr detector under consideration is 100 kton.

TABLE 1. Sensitivities to a non-zero $\sin^2 2\theta_{13}$, CP violation and the mass hierarchy at the 3σ level for a WCh detector in the WBLE beam (WCh-W), a LAr detector in the WBLE (LAr-W) and NuMI off-axis beam (LAr-N). Limits are obtained after a total exposure of 6×10^{21} PoT equally divided among ν and $\bar{\nu}$ running.

	$\sin^2 2\theta_{13} \neq 0$	CP violation	mass hierarchy
WCh-W	0.006	0.03	0.01
LAr-W	0.003	0.005	0.006
LAr-N	0.002	0.03	0.05

SENSITIVITY CALCULATIONS

Three limits as a function of true $\sin^2 2\theta_{13}$ and δ_{cp} are derived for each experimental variation: sensitivity to a non-zero $\sin^2 2\theta_{13}$, CP violation and resolving the mass hierarchy. When single value limits are quoted, this corresponds to the value of $\sin^2 2\theta_{13}$ above which the sensitivity is better than the quoted confidence level for 50% of the δ_{cp} phase space. For a limited set of $(\sin^2 2\theta_{13}, \delta_{cp})$ combinations, the ability to measure these values is also explored. Correlations between oscillation parameters are taken into account.

The values of the atmospheric mixing parameters were chosen to be $|\Delta m^2_{31}| = 2.7\times10^{-3} eV^2$ and $\sin^2 2\theta_{13} = 1$, with the error determined from the ν_μ disappearance channel. The solar parameters are set to $\Delta m^2_{21} = 8.6\times 10^{-5}$ and $\sin^2 2\theta_{12} = 0.86$, both with an error of 5%. The error on the matter density is taken to be 5%, while the error on the background is assumed to be 10%.

The obtained limits for each experiment described above are listed in table 1. The overall best performance is obtained with a LAr detector placed in the WBLE beam. When placed in the NuMI off-axis beam, the sensitivity to CP violation is still good, but the ability to determine the mass hierarchy is much worse. The WCh detector performs good for all three hypotheses tested.

The sensitivity to the mass hierarchy as function of true $\sin^2 2\theta_{13}$ and δ_{cp} is shown in figure 2 for the LAr detector. The dependence on δ_{cp}, which is already small, can be further reduced by running longer in anti-neutrino mode.

As shown in figure 3, $\sin^2 2\theta_{13}$ can be measured to 10% at 68% C.L. with a WCh detector for values larger than 0.01 independently of δ_{cp} in the case of normal hierarchy. For a LAr detector in the WBLE beam, this number decreases to 6%. The errors are very similar if the true mass hierarchy turns out to be inverted.

Background Uncertainties and Exposure

The sensitivities for a WCh detector excluding systematic errors are listed in table 2. It is clear that the CP ex-

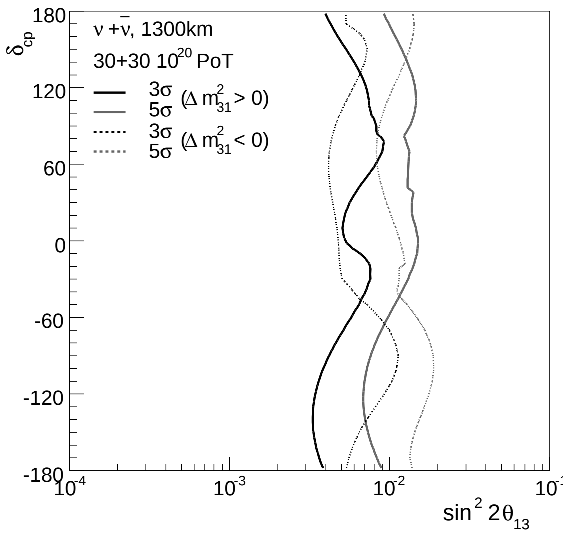

FIGURE 2. The sensitivity to the mass ordering for a LAr detector exposed to a total of $6 \cdot 10^{21}$ PoT producing the WBLE beam. For true values of $\sin^2 2\theta_{13}$ and δ_{cp} to the right of the solid (dotted) lines, the inverted (normal) mass hierarchy can be excluded. The black (gray) lines show the sensitivity at the 3σ (5σ) level.

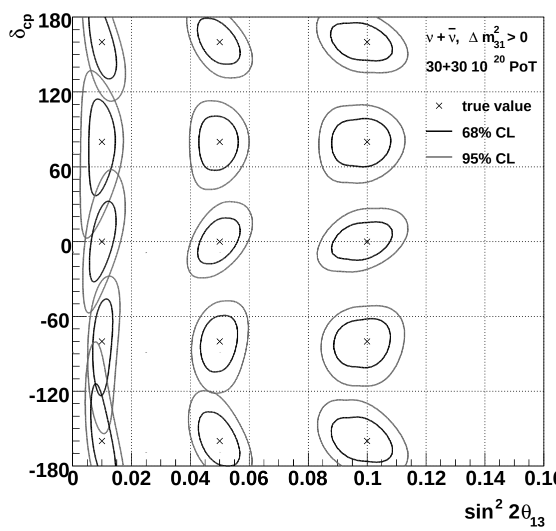

FIGURE 3. The measurement of $\sin^2 2\theta_{13}$ and δ_{cp} for a WCh detector assuming an exposure to 6×10^{21} PoT. The true input values are indicated by the crosses, while the contours are shown at 68% (black) and 95% (gray) confidence level.

clusion limit is most affected by the background uncertainty. This measurement can benefit significantly if this uncertainty can be reduced to 5%. This seems perfectly reasonable as it is almost certain a near detector will be deployed which will measure the background contamination to high precision. Table 2 also shows the results

TABLE 2. Sensitivities for a WCh detector under different assumptions: I) statistics only, II) a 5% uncertainty on the background and III) same as II but for twice the running time, i.e. 6×10^{21} PoT for neutrino and anti-neutrino running each.

	$\sin^2 2\theta_{13} \neq 0$	CP violation	mass hierarchy
I	0.005	0.01	0.01
II	0.005	0.02	0.01
III	0.004	0.01	0.008

when the exposure is doubled.

CONCLUSIONS

Details of the sensitivity calculations performed in the scope of the joint FNAL-BNL U.S. long baseline neutrino experiment study were discussed. The best limits for the same exposure are obtained using a 100 kton LAr detector in the WBLE beam. Placing this detector off-axis in the NuMI beam reduces the sensitivity to the mass hierarchy significantly. The 300 kton WCh detector placed at the DUSEL candidate site has a good overall performance. It was also shown that this detector is not limited by background systematics if controlled to better than 5%.

ACKNOWLEDGMENTS

I am grateful to Brookhaven National Laboratory for supporting the work presented. I want to thank everybody involved in this study for their valuable input, and in particular Milind Diwan and Mary Bishai for their fruitful discussions.

REFERENCES

1. F. Ardellier, et al. (2006), `hep-ex/0606025`.
2. X. Guo, et al. (2007), `hep-ex/0701029`.
3. Y. Itow, et al. (2001), `hep-ex/0106019`.
4. D. S. Ayres, et al. (2004), `hep-ex/0503053`.
5. V. Barger, et al. (2007), `arXiv:0705.4396 [hep-ph]`.
6. Supporting documentation and material can be found at http://nwg.phy.bnl.gov/fnal-bnl
7. P. Huber, M. Lindner, and W. Winter, *Comput. Phys. Commun.* **167**, 195 (2005).
8. D. G. Michael, et al., *Phys. Rev. Lett.* **97**, 191801 (2006).
9. C. Yanagisawa, C. K. Jung, P.T. Le, and B. Viren, see [6].
10. F. Dufour, and E. Kearns, see [6]
11. R. Brun, et al., CERN Program Library Long Writeup W5013 (1994).
12. D. Casper, *Nucl. Phys. Proc. Suppl.* **112**, 161 (2002).
13. C. Bromberg, et al., (2002) `Fermilab-FN-0776-e`, see [6].