

# Long-Baseline Neutrino Experiment (LBNE): Science and Sensitivity.

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for the LBNE Science Collaboration Executive Committee.  
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The following is in response to the question posed by the JOG working group attached to this note.

Assuming the minimal picture for massive neutrinos the most important goals of the next phase of neutrino experiments are:

- (i) To determine the electron neutrino content in neutrino 3, or the value of  $\sin^2\theta_{13}$ , as precisely as possible, since this could be a powerful indicator of the underlying nature of the mixing patterns.
- (ii) To determine the sign of  $\Delta m^2_{31}$ , or the character of the neutrino mass ordering;
- (iii) To improve the accuracy of the measurement of the other mixing angles and the mass squared differences;
- (iv) To probe the existence of CP violation and measure the value of the CP violating phase,  $\delta_{CP}$ , to test the plausibility of neutrinos as the origin of the matter/antimatter asymmetry in the universe.

The Long-Baseline Neutrino Experiment (LBNE) is the most sensitive experiment in the world for making the above measurements, however the main focus is on the measurement of CP violation.

The project consists of at least two modules of 100 kton water Cherenkov equivalent (WCE) detectors and an intense beam from Fermi National Accelerator Laboratory to the Deep Underground Science and Engineering Laboratory over a distance of 1300km. It searches for electron neutrino appearance in an almost pure muon neutrino beam. The detector requirement could be satisfied by either modules of water Cherenkov detectors or liquid argon time projection chambers (TPC), that have a mass about 1/6 of the total water Cherenkov mass. The sensitivity of LBNE for measuring the crucial parameters,  $\theta_{13}$  and  $\delta_{CP}$  is displayed in Figs. 1 and 2. The sensitivity to  $\theta_{13}$  is displayed in terms of  $\sin^2 2\theta_{13}$ . In addition, Fig. 3 shows the sensitivity of LBNE to determine the mass ordering as a function of  $\sin^2 2\theta_{13}$ .

Figure 1 shows the expected result of the measurement of  $\nu_{\mu} \rightarrow \nu_e$  oscillations with a 200 kton water Cherenkov detector, a 700 kW beam operated for 10 yrs, and

running times split equally between neutrinos and antineutrinos. Since the appearance probability depends on both  $\theta_{13}$  and  $\delta_{CP}$ , non-observation yields a correlated limit as shown in the solid curve in Fig. 1. The region to the right of the solid curve is excluded at a 90% confidence level, including both statistical and systematic errors. The limit resulting from statistical errors only is also shown. Even after this long running period, the sensitivity is dominated by statistical errors. Figure 1 also shows the result of a definite observation at an example small value of  $\sin^2 2\theta_{13} = 0.01$  and  $\delta_{CP} = -90$  deg. The dotted oval represents the determination of these parameters at 90% C.L. The measurement of  $\delta_{CP}$  would be a factor two better at larger values of  $\sin^2 2\theta_{13}$ . The results for the same running time with a 34 kton liquid argon TPC are similar. This calculation assumes that the third neutrino is heavier than the other two. If it is lighter, then the limit is slightly weaker, but the measurement at the example point will be similar.

The sensitivity for  $\theta_{13}$  as a function of running time is plotted in Fig. 2, which shows the 90% confidence upper bound on  $\sin^2 2\theta_{13}$ , for the hypothesis of  $\theta_{13} = 0$ , as a function of exposure for a water Cherenkov detector (bottom scale) and a liquid argon TPC (top scale). These limits assume a 700 kW beam, with running time split equally between neutrinos and antineutrinos. The exposure is expressed in terms of the product of detector mass (kton) and running time (years) for water Cherenkov and liquid argon detectors. The solid line shows the limit assuming  $\delta_{CP} = 0$ , and the upper and lower curves indicate the maximum and minimum of the range of the limit on  $\sin^2 2\theta_{13}$  for the full range of  $\delta_{CP}$ . The sensitivity at  $\delta_{CP} = 0$  is also shown with statistical errors only in the dashed line. Since this is a search for  $\nu_e$  appearance in an almost pure  $\nu_\mu$  beam, the sensitivity of LBNE for  $\theta_{13}$  is expected to be limited mainly by statistical errors up to very large exposures and small values of  $\theta_{13}$ . As with the case illustrated in Fig. 1, this calculation assumes that the third neutrino is heavier than the other two; slightly weaker limits would be set assuming the opposite mass ordering.

If LBNE finds no evidence for a non-zero value of  $\theta_{13}$  in 10 years of data taking, it will be capable of setting limits on  $\sin^2 2\theta_{13}$  in the range of  $1-5 \times 10^{-3}$ , correlated to the value of  $\delta_{CP}$ . If  $\theta_{13}$  is non-zero, then for the same running period, LBNE will be capable of a  $3\sigma$  observation for  $\sin^2 2\theta_{13}$  in the range of  $3-8 \times 10^{-3}$ , depending on the value of  $\delta_{CP}$ . If we assume that the reactor experiments will be able to reach a limit of  $8 \times 10^{-3}$ , which is subject to the ultimate systematic error in those experiments, the LBNE sensitivity would exceed that of any other experiment currently planned by a factor of 2.5 averaged over the value of  $\delta_{CP}$ . For  $\sim 80\%$  of the  $\delta_{CP}$  range LBNE would be sensitive to values smaller than  $3 \times 10^{-3}$ . In contrast to the reactor experiments, the ability of LBNE to constrain  $\theta_{13}$  is mainly limited by statistical, not systematic errors, and therefore the limits can be substantially improved by greater

exposure, as shown in Fig. 2, by longer running, increased beam power, or increased detector mass.

Finally, LBNE beam and running conditions are optimized for measurement of  $\delta_{CP}$  and the mass ordering. LBNE capability to measure  $\delta_{CP}$  and the mass ordering is unmatched by any current experiment. Indeed, for  $\sin^2 2\theta_{13}$  less than 0.15, it is the only experiment capable of unambiguously determining the mass ordering for all values of  $\delta_{CP}$ . If LBNE were to be re-optimized for limiting  $\theta_{13}$  to very small values, then the strategy would need re-examination.

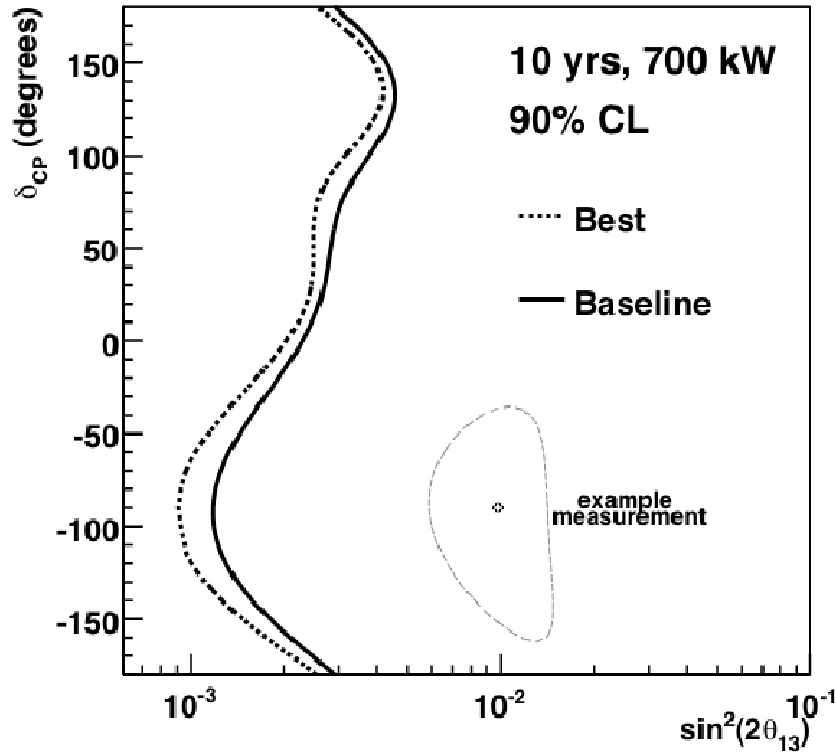


Figure 1. 90% confidence level upper bound on the correlated values of  $\sin^2 2\theta_{13}$  and  $\delta_{CP}$  in the case that the observed number of  $\nu_e$  events are consistent with backgrounds, for 10 years of operation with a 700 kW beam, split equally between neutrino and antineutrino running, with a 200 kton water Cherenkov Detector. The limit for a 34 kton liquid Argon TPC is similar. The limit (Baseline) includes both statistical and systematic errors; the dashed curve (Best) shows the statistics only limit for comparison. In the case of a definite observation, the dotted oval shows a 90% confidence level interval at example values of  $\sin^2 2\theta_{13} = 0.01$  and  $\delta_{CP} = -90$  deg. This calculation assumes that the third neutrino is heavier than the other two.

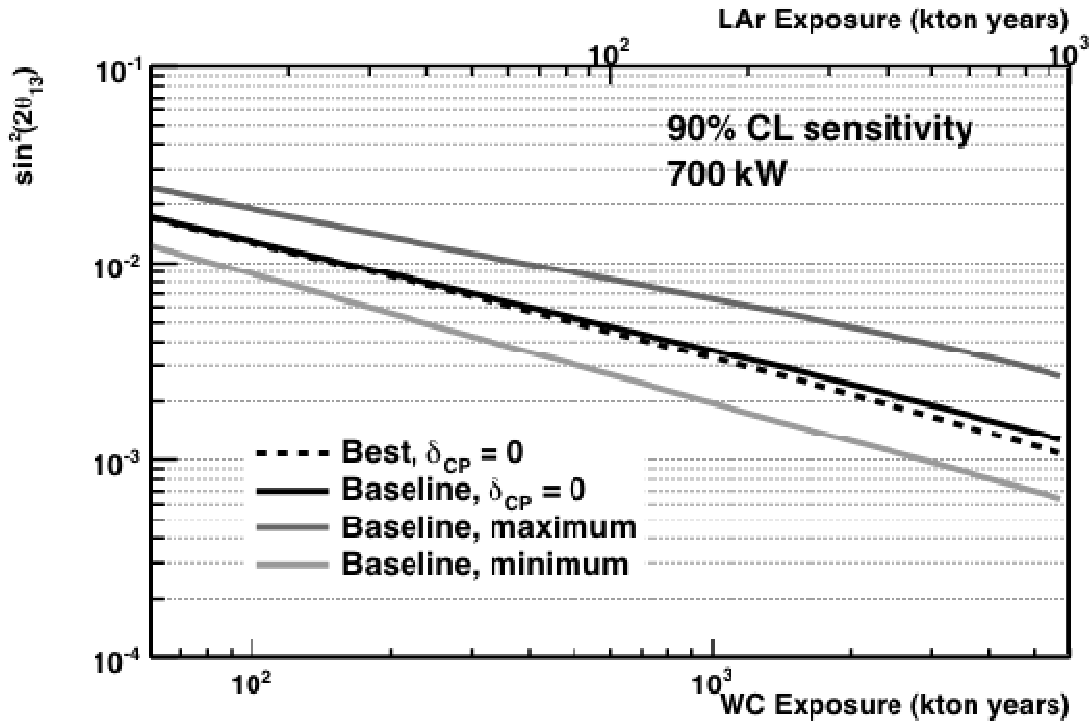


Figure 2. 90% confidence upper bound on  $\sin^2 2\theta_{13}$  in the case of  $\nu_e$  events being consistent with the expected backgrounds as a function of exposure with a Water Cherenkov Detector (bottom scale) or LAr detector (top scale), for 10 years of operation with a 700 kW beam, split equally between neutrino and antineutrino running. The scales are in the units of kton times years. The solid line (Baseline) includes both statistical and systematic errors and shows the limit for the case of  $\delta_{CP} = 0$ , and the light curves indicate the maximum and minimum of the range of the limit on  $\sin^2 2\theta_{13}$  for the full range of  $\delta_{CP}$ . The dashed curve (Best) shows the limit at  $\delta_{CP} = 0$  considering statistical uncertainties only. This calculation assumes that the third neutrino is heavier than the other two.

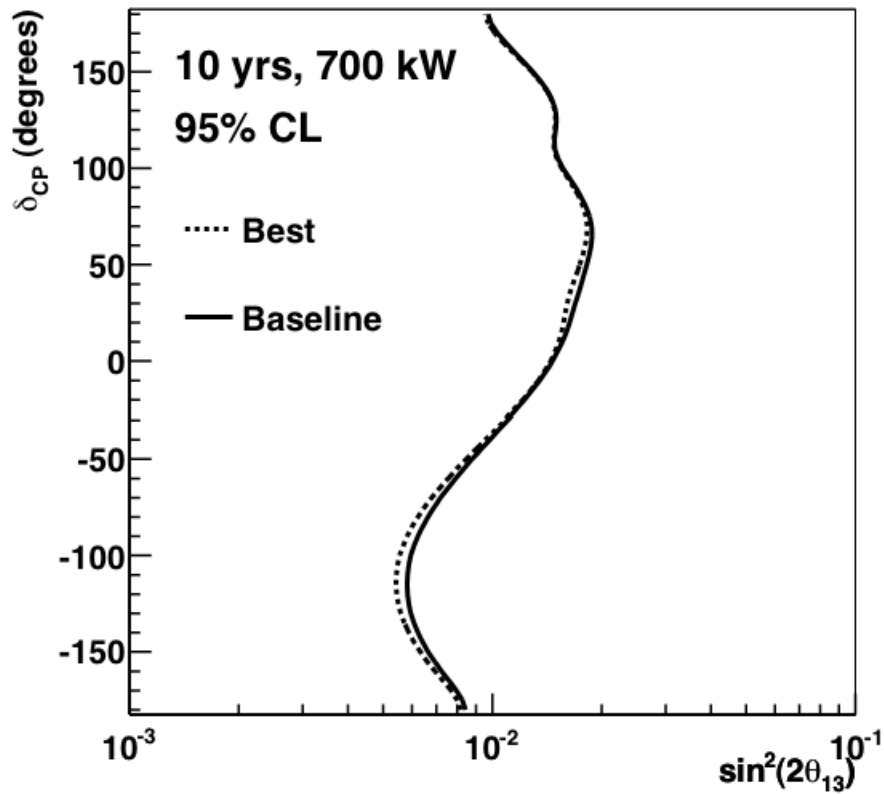


Figure 3. The minimum correlated values of  $\sin^2 2\theta_{13}$  and  $\delta_{CP}$  at which the mass ordering can be determined at a 95% confidence level for 10 years of operation with a 700 kW beam, split equally between neutrino and antineutrino running, with a 200 kton water Cherenkov Detector. The limit for a 34 kton liquid Argon TPC is similar. This confidence level is chosen for comparison with NOvA. It is considered adequate for a discovery in mass hierarchy which is a binary decision. The solid line (Baseline) includes both statistical and systematic errors; the dashed curve (Best) includes the statistics errors only. This calculation assumes that the third neutrino is heavier than the other two; if it is lighter the curve has different behavior as a function of  $\delta_{CP}$ , but the overall sensitivity is roughly the same.

**Subject:** LBNE's reach for theta\_13

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Jim, Gina, Milind, Bob:

The agencies are in need of a crisp, coherent statement, sanctioned by the community, on the reach in theta\_13 of the LBNE experiment as currently configured. We assume this includes both technology options. We realize that you have made some progress on this front, but before we can formally address the questions we are getting, we need a single, brief statement on the issue, endorsed by the community. We expect this statement to reflect the thinking of both the project and the collaboration.

In order to properly prepare ourselves for upcoming events in Washington, we will need a short white paper from you outlining the assumptions and results by Tuesday, August 17. Please call me if you have any questions.

Thanks very much – we'll expect to hear from you --

Mike, Eli, Jon, David, Steve  
JOG LBNE Working Group