A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEδALUS

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Abstract: This study presents comparative CP sensitivities for various sets of water Cerenkov and liquid argon detectors combined with various running scenarios associated with DAEδALUS and LBNE neutrino beams at DUSEL. LBNE-only running scenarios show fairly small differences in sensitivity for the various detector combinations. On the other hand, the DAEδALUS-only and DAEδALUS-plus-LBNE running gives significantly better sensitivity for a detector combination that includes at least 200 kt of Gd-doped water Cerenkov detector, exceeding the sensitivity of a Project-X 10 year run. A 300 kt Gd-doped water Cerenkov detector yields the best sensitivity for combined running.

This study examines the sensitivity of various design configurations proposed for DUSEL for the physics of CP violation. We rank-order ten configurations of beams and detectors. We consider three types of detector “units” which are then arranged in configurations consisting of sets of three units. The units are:

- **WCGd**: 100 kt Gd-doped water Cerenkov detector with \( \approx 20\% \) high quantum efficiency PMT coverage and/or light concentrators to realize good efficiency for the \( \sim 5 \text{ MeV} \) Cerenkov light signal expected from neutron capture on Gd [1];

- **WC**: 100 kt water Cerenkov detector modules with 15% high quantum efficiency PMT coverage;

- **LAr**: 17 kt of LAr.

We consider three types of neutrino sources, with 10 year running-periods:
• **LBNE alone** – which is $30 \times 10^{20}$ protons on target (POT) in neutrino mode followed by $30 \times 10^{20}$ POT in antineutrino mode. This is the standard 10-year run-plan prior to the startup of Project X [2].

• **DAEδALUS alone** – which is in antineutrino mode, following the plan described in ref. [3].

• **DAEδALUS + LBNE** – which is the standard plan for DAEδALUS antineutrino running combined with LBNE running for the full 10 years in only neutrino mode. These programs can proceed simultaneously.

The code used for this study is described in detail in ref. [3]. The DAEδALUS event rates do not depend on the mass hierarchy, but the LBNE rates do; for this study we use the normal hierarchy. For these comparisons, an input uncertainty of $\delta(\sin^2 2\theta_{13}) = 0.005$ from the upcoming reactor experiments, has been assumed [3, 4, 5].

The assumptions concerning beam fluxes for DAEδALUS and LBNE have been described in ref. [3]. The DAEδALUS flux assumes a decay at rest (DAR) beam arising from the stopped pion decay chain produced by an incident proton beam of 800 MeV. The assumed locations and powers of the sources are: 1 MW at 1.5 km, 2 MW at 8 km, and 5 MW (when time averaged across the 2-phase run-plan) at 20 km. The LBNE flux files used in this discussion are [6]:

- dusel120e250i002dr280dz1300km_flux.txt (neutrino flux)
- dusel120e250ni002dr280dz1300km_flux.txt (antineutrino flux)

These files are for an 120-GeV proton-on-target, on-axis, NuMI-like beam with a 280-m decay.

Refs. [3], [4] and [7] describe the assumptions related to signal events and backgrounds in the water Cerenkov detector for both the DAEδALUS and LBNE running. We assume a 67% reconstruction efficiency for DAEδALUS inverse beta decay signal events in a WCGd. We assume a 15% reconstruction efficiency for LBNE charged current quasielastic signal events in either WC or WCGd. DAEδALUS event backgrounds arise from beam-off sources, which can be measured during beam-off, and from intrinsic $\bar{\nu}_e$ in the beam, which is measured by the near accelerator. The systematics on these backgrounds arise from the statistical error on the measurements. LBNE event backgrounds arise from neutral current (NC) misidentification and intrinsic
electron-flavor neutrinos in the beam. In the WC detector, we assume a 10% error on the LBNE NC and intrinsic backgrounds.

In this study, we also consider an LAr detector option. Because this target has no free protons, there is a low interaction rate for a DAR beam, and this detector does not contribute to the DAEδALUS event sample. However, this detector can efficiently observe interactions at LBNE beam energies. To address the fact that the LAr detector has better signal to background for NC mis-identification, we scale the WC mis-identification background for each LAr unit. The assumption is that the overall efficiency for electron neutrinos or antineutrinos for LAr is 90%, which is 6 times higher than WC. The efficiency for accepting neutral current π⁰ background is unchanged, so that this effectively gives a reduction factor for neutral current π⁰ background of 6 (to 17% of the WC). These scale factors are consistent with the present assumptions of the LBNE collaboration [8] and other studies [9, 10]. To be specific, for this study, we assume:

- 3×WC = 1.0*background,
- 2×WC + 1×LAr = 0.72*background,
- 1×WC + 2×LAr = 0.44*background,
- 3×LAr = 0.17*background,

where “background” refers to the mis-identification background for signal events produced by the LBNE beam.

As a simple benchmark to compare scenarios, we choose a point in (\sin^2 2\theta_{13}, \delta_{CP}) space and report the 1σ error on \delta_{CP} for each configuration. We have chosen (\sin^2 2\theta_{13} = 0.05, \delta_{CP} = -90°). A comparison of ten scenarios is made in Table 1, ranked according to increasing sensitivity (1 is worst, 10 is best).

In the case of running DAEδALUS alone, only the number of units of WCGd are relevant, because the WC and LAr units are not sensitive to DAEδALUS events. Table 1 shows that running DAEδALUS alone with only 1 WCGd unit has poorest sensitivity (rank=1). As this configuration is statistics limited, adding units of WCGd immediately increases DAEδALUS' sensitivity. Two units of WCGd are already better than running LBNE alone (rank= 5) and 3 WCGd units is best for DAEδALUS alone (rank=7). The 3 WCGd unit is also the best for the combined beams (rank=10).
| Rank | Source                          | Configuration                   | 1σ error | Comment |
|------|---------------------------------|---------------------------------|----------|---------|
| 1.   | DAEδALUS alone                  | 1×WCGd                          | 34°      | Worst   |
| 2.   | LBNE alone                      | 3×WC                            | 25°      |         |
| 3.   | LBNE alone                      | 2×WC+1×LAr                      | 24°      |         |
| 4.   | LBNE alone                      | 1×WC+2×LAr                      | 23°      |         |
| 5.   | DAEδALUS alone                  | 2×WCGd                          | 22°      |         |
| 6.   | DAEδALUS + LBNE                 | 1×WCGd+2×WC                     | 18°      |         |
| 7.   | DAEδALUS alone                  | 3×WCGd                          | 17°      |         |
| 8.   | DAEδALUS + LBNE                 | 2×WCGd+1×WC                     | 15°      |         |
| 9.   | DAEδALUS + LBNE                 | 2×WCGd+1×LAr                    | 15°      |         |
| 10.  | DAEδALUS + LBNE                 | 3×WCGd                          | 13°      | Best    |

Table 1: Comparison of Configurations for $\sin^2 2\theta_{13} = 0.05$ and $\delta_{CP} = -90^\circ$

The sensitivities for running LBNE alone are very similar for the various configurations (ranks = 2-4). This is simply a statement that the LAr sensitivity is designed to match the WC sensitivity by balancing target size against efficiency. Three configurations of WC and LAr units are provided. Note that WC and WCGd are equivalent in the case of LBNE. This is because the LBNE beam energy is > 100 MeV; in this range neutron capture is no longer a relevant tag.

The best sensitivities arise when the two beam sources are combined with at least 200 kt of Gd-doped water Cerenkov detector. For a discussion of how the beams are complementary, resulting in this substantial improvement in sensitivity, see refs. [3] and [11]. For the combined source running, the case of 1 WCGd module and 2 WC modules (rank=6) is significantly worse than the cases of 2 WCGd modules and 1 WC or 1 LAr (ranks =8 and 9). As discussed above, the best sensitivity arises from 300 kt of Gd-doped water Cerenkov detector (rank=10).

The conclusions of Table 1 follow for all values of $\delta_{CP}$. To see this, we provide plots which show the comparisons across all values of $\delta_{CP}$, for $\sin^2 2\theta_{13} = 0.05$, in Figures 1 to 4.

Figure 5 shows the fraction of non-zero (and non-180°) $\delta_{CP}$-space which can be sampled at 3σ. For simplicity, only the designs which ranked 6, 9 and 10 in Table 1 are shown. This allows comparison for the best cases for 100 kt, 200 kt and 300 kt WCGd. The Project X expectation is also shown. This assumes a 300 kt set of WC detectors with the LBNE conventional beam
for $10^{22}$ POT in neutrino mode and $10^{22}$ POT in antineutrino mode. Both the 200 kt and 300 kt designs, paired with the combined DAEδALUS-plus-
LBNE-$\nu$-only neutrino source, exceed the Project X expectation [3, 11].

In conclusion, the reach of the combined LBNE and DAEδALUS beams is outstanding, when at least 200 kt of Gd-doped water Cerenkov detector is included in the plan. The 300 kt design provides the best sensitivity.
Figure 1: The $\delta_{CP}$ measurement sensitivity at 1$\sigma$ for LBNE-only running for various configurations as a function of $\delta_{CP}$. Each measurement is for 5 years of $\nu$ plus 5 years $\bar{\nu}$ running.
300kt Water Cerenkov (10 years)  
(with various amounts of Gd loaded tonnage for Daedalus)  
- Gd loading does not affect LBNE so always 300kt WC -

Figure 2: The $\delta_{CP}$ measurement sensitivity at 1$\sigma$ as a function of $\delta_{CP}$ for various configurations involving units of WC and WCGd which total 300 kt. The DAE$\delta$ALUS-only and DAE$\delta$ALUS plus LBNE $\nu$–only scenarios are for 10 years of running and the LBNE-only is for 5 years of $\nu$ plus 5 years $\bar{\nu}$ running.
Figure 3: The $\delta_{CP}$ measurement sensitivity at $1\sigma$ as a function of $\delta_{CP}$ for various configurations involving units of LAr, WC and WCGd, with 200 kt of WCGd. One example of only 100 kt of WCGd is also shown. The DAE$\delta$ALUS-only and DAE$\delta$ALUS plus LBNE $\nu$–only scenarios are for 10 years of running and the LBNE-only is for 5 years of $\nu$ plus 5 years $\bar{\nu}$ running.
Figure 4: The $\delta_{CP}$ measurement sensitivity at 1$\sigma$ as a function of $\delta_{CP}$ for various configurations involving units of LAr, WC and WCGd, with only 100 kt of WCGd. The DAE$\delta$ALUS-only and DAE$\delta$ALUS plus LBNE $\nu$-only scenarios are for 10 years of running and the LBNE-only is for 5 years of $\nu$ plus 5 years $\bar{\nu}$ running.
Figure 5: The fraction of $\delta_{CP}$-space which excludes $0^\circ$ or $180^\circ$ at 3$\sigma$ for various configurations involving units of LAr, WC and WCGd assuming DAE$\delta$ALUS plus LBNE $\nu$—only scenarios for 10 years of running. Three examples, ranked 6, 9 and 10 in Table 1, with 100 kt (blue diamond), 200 kt (purple triangle) and 300 kt of WCGd (bold red line), are presented. In each case, the LBNE running is with three modules, either 3 WC or 2 WC plus 1 LAr – thus LBNE events come from 300 kt-equivalent in all three cases. These are compared with the Project X sensitivity (black x) and the standard LBNE-only run, both of which employ 5 years of $\nu$ plus 5 years $\bar{\nu}$ running with three modules, 300 kt WC.
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