Snowmass2021 - Letter of Interest

Long-Baseline Neutrinos at THEIA

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract:

THEIA is a proposed Water-based Liquid Scintillator (WbLS) detector that is sensitive to a broad range of physics, including solar neutrinos, supernova neutrinos, atmospheric neutrinos, and proton decay. If located at the Sanford Underground Research Facility (SURF), THEIA can also perform a precise measurement of long-baseline neutrino oscillation parameters with a complementary detector technology and target nucleus to the DUNE liquid argon detectors. Recent advancements in reconstruction for water Cherenkov detectors have substantially increased the long-baseline sensitivity of such a detector, and the expected sensitivity of THEIA to both δ_{CP} and the neutrino mass hierarchy, if placed in the soon-to-be excavated 4th LBNF cavern at SURF, is similar to that of a corresponding DUNE far detector module.

THEIA achieves a broad range of physics by exploiting new technologies to act simultaneously as a (low-energy) scintillation detector and a (high-energy) Cherenkov detector. Scintillation light provides the energy resolution necessary to constrain or reject the majority of radioactive backgrounds and provides the ability to see slow-moving recoils; Cherenkov light enables event direction reconstruction, which provides particle ID at high energies and background discrimination at low energies. Together, these capabilities enable a wide range of physics deliverables, including a sub-10% measurement of the solar CNO flux, enhanced detection of supernova burst neutrinos with a pointing accuracy of 1° for a galactic supernova, sensitivity for a 5σ measurement of the Diffuse SuperNova Background (DSNB), and sensitivity to neutrinoless double beta decay down to a mass of 5 meV [1].

If THEIA is placed at the Sanford Underground Research Facility (SURF), it can also make measurements of neutrino oscillations from the Long-Baseline Neutrion Facility (LBNF) neutrino beam produced at Fermilab. Two detector sizes have been considered: a 25 kt detector (THEIA25) with a 17 kt fiducial volume, and a 100 kt detector (THEIA100) with a 70 kt fiducial volume. LBNF is planning to excavate 4 detector caverns at SURF, and THEIA25 is designed to fit inside the 4th, as yet unoccupied, cavern. THEIA100 would require a dedicated, upright-cylinder-shaped cavity.

The primary physics goal of the DUNE experiment is to measure the CP-violating phase, δ_{CP}, of the PMNS mixing matrix, as well as other oscillation parameters, such as θ_{23} and the mass squared splitting Δm^2_{32}, and the neutrino mass hierarchy [2]. A THEIA detector placed at SURF can provide sensitivity to these parameters similar to a comparably-sized liquid argon detector. The ability to measure long-baseline neutrino oscillations with a distinct set of detector systematic uncertainties and neutrino interaction uncertainties relative to the liquid argon detectors, would provide an important independent validation of the extracted oscillation parameter values.

Previous studies of a water Cherenkov detector in the LBNF beam were performed in the context of the predecessor experiment to DUNE: LBNE [3]. These studies were based on Super-Kamiokande event reconstruction techniques developed within the first several years of Super-Kamiokande data taking, and were restricted to single-ring events with no detected Michel electrons from stopped pion and muon decay. In the decade since, important advancements have been made in Cherenkov reconstruction that have substantially improved particle identification and ring counting. The FiTQun event reconstruction package used for THEIA sensitivity studies has now been fully implemented in the most recent T2K analyses [4]. These improvements, when applied to the LBNF beam, enhance the sensitivity to neutrino oscillations in three important ways:

1. The improved ring counting has removed 75% of the neutral current background, relative to the previous analysis, due to improvements in the detection of the faint second ring in boosted π^0 decays;
2. The improved electron/muon particle identification has allowed for an additional sample of 1-ring, zero Michel electron events from ν_3-CCπ^+ interactions, without significant contamination from ν_μ backgrounds
3. Multi-ring ν_e event samples can now be selected with sufficient purity to further enhance sensitivity to neutrino oscillation parameters.

In the LBNE analysis [3], a single ν_e Charged Current (CC) sample was used, which required no late-time Michel electron signals to further reduce the ν_μ-CC background. In this analysis, using the improved e/μ particle identification capabilities of FiTQun, it is possible to include an additional sample of ν_e-CC events with 1 decay electron to include CC1π^+ events with very low ν_μ-CC background. In addition, 2- and 3-ring ν_e-CC samples are included in both the neutrino and antineutrino beam running configurations. In total, there are now 9 ν_e-CC event samples:

- Neutrino beam mode: 1-, 2-, and 3-ring samples with 0 or 1 Michael electron signal.
- Antineutrino beam mode: 1-, 2-, and 3- ring samples with 0 decay electron signals.

An analysis with GLoBES [5, 6], with comparable systematic uncertainties to thosed used in the DUNE Conceptual Design Report (CDR), was performed. The resulting sensitivities are shown in Figure 1. The 17 kt fiducial volume of THEIA25 provides sensitivities to δ_{CP} and the mass hierarchy that are similar to a DUNE 10 kt (fiducial) liquid argon detector.

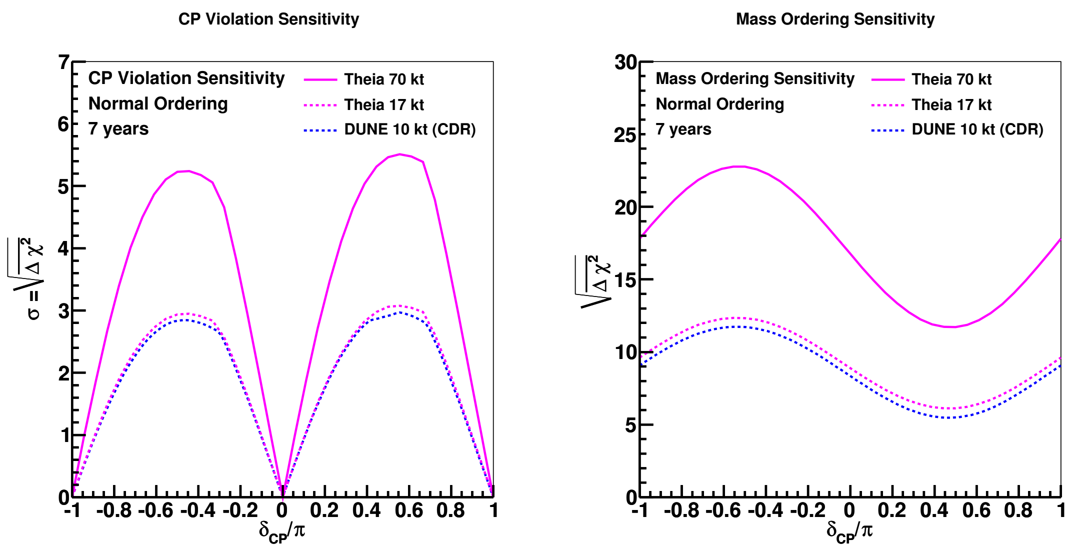

FIG. 1. Sensitivity to CP violation (i.e.: determination that $\delta_{CP} \neq 0$ or π) (left) and sensitivity to determination of the neutrino mass ordering (right), as a function of the true value of δ_{CP}, for the THEIA 70-kt fiducial volume detector (pink). Also shown are sensitivity curves for a 10-kt (fiducial) LArTPC (blue dashed) compared to a 17-kt (fiducial) WCD (pink dashed). Seven years of exposure to the LBNF beam with equal running in neutrino and antineutrino mode is assumed. LArTPC sensitivity is based on detector performance described by [7].

The reference design in the upcoming DUNE Near Detector Conceptual Design report includes a 3D scintillator tracker (3DST) [2], which consists of the same 1 cm^3 scintillator cube design as that of the Super-FGD upgrade for the T2K near detector [8]. The 3DST can function as a high-precision near detector for THEIA, just as the Super-FGD was designed as a near detector for Super-Kamiokande.

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