Phase II of the DUNE Experiment: Scientific Opportunities, Detector Concepts and Technological Challenges

The DUNE Collaboration

April 2023

Contents

1 DUNE and the Elements of DUNE Phase II

The DUNE at the Long-Baseline Neutrino Facility (LBNF) was conceived in 2015, following the recommendations of the 2013 update of the European Strategy for Particle Physics [1] and of the 2014 Report of the US Particle Physics Project Prioritization Panel (P5) [2]. The 2014 P5 Report recommended developing, in collaboration with international partners, a coherent long-baseline neutrino program hosted at Fermilab, with a mean sensitivity to CP violation of better than 3σ over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. Estimates at the time suggested that a 600 kt·MW·yr exposure at the Far Detector (FD) would be needed in order to reach this goal[1], together with a control of systematic uncertainties at the percent level thanks to near detector (ND) data constraints. The 2014 P5 Report also recommended a broad program of neutrino astrophysics and physics beyond the Standard Model (BSM) as part of DUNE, including demonstrated capability to search for supernova (SN) bursts and for proton decay. Likewise, the 2013 Update of the European Strategy for Particle Physics and its 2020 Update recommended the Europe and CERN (through its Neutrino Platform) should continue to collaborate towards the successful implementation of LBNF and DUNE.

Today, the vision put forward by the above strategic recommendations is still very appropriate and timely. The DUNE Collaboration and the LBNF team have made major progress toward the realization of this project, with the aim to start the scientific exploitation in 2029. Based on recent estimates, the ultimate CP violation measurement goal put forward by the 2014 P5 Report should be reachable with an exposure of about 1000 kt·MW·yr, or about 15 years of physics data-taking. DUNE's neutrino astrophysics and BSM physics programs also require operations for at least 15 years, until the 2045 timeframe and possibly beyond.

For the successful implementation of DUNE/LBNF, the full extent of the available resources and funding profiles, a realistic estimate of the project costs, and a clear understanding of the

[1]The exposure is expressed here as the product of FD fiducial mass, beam power and FD exposure time.

distribution, and relatedly, a dramatic reduction in energy losses to impurities such as nitrogen that would result from non-radiative energy transfers involving the long-lived triplet state of Ar that is suppressed with the introduction of Xe. This leads to much improved robustness of the scintillation light yield against LAr impurities, without appreciable impact on the charge signal. Xe doping up to $\sim$ 20 ppm has been demonstrated with ProtoDUNE-SP, which verified the enhancements to optical response and the recovery of light yield in the presence of impurities using a 770 ton single-phase LArTPC functionally identical to the DUNE Phase I single-phase FD [36].

At higher concentrations, up to the percent level, Xe may also be of interest as a signal source. 136Xe is a candidate isotope for neutrinoless double-beta decay (NLDBD), which if observed would establish the Majorana nature of the neutrino and demonstrate a violation of lepton number conservation [38]. The introduction of Xe either in its natural form (8.9% 136Xe) or enriched in the NLDBD isotope into a large-scale, deep-underground LArTPC detector could provide an opportunity to search for this important decay mode [39]. Mitigation of important backgrounds (^{39}Ar, ^{42}Ar, neutrons) near the 2.5 MeV Q-value for this decay are consistent with the requirements of other potential low-energy physics goals considered for DUNE Phase II, as described in Section 3.3. A key challenge for a competitive search is achieving an energy resolution at the percent level for MeV-scale electrons; photosensitive dopants provide one avenue toward achieving this.

3.4.2 Water-based (Gabriel)

Theia is the only concept for FD3/4 with a demonstrated ability to probe a rich program of physics beyond the core DUNE program. Theia offers world-leading science in particle, nuclear and astrophysics, with proven, demonstrated technology.

Hybrid detection concept Theia is a proposed hybrid optical detector, capable of separating scintillation and Cherenkov light via use of Water-based Liquid Scintillator (WbLS), fast timing, and spectral sorting. Operating deep underground, Theia would open up new areas of science, as detailed in the White Paper [**?**] and summarized below.

Cherenkov light offers electron / muon discrimination at high energy via ring imaging, and sensitivity to particle direction at low energy. The scintillation signature offers improved energy and vertex resolution, particle identification (PID) capability via species-dependent quenching effects on the time profile, and low-threshold (sub-Cherenkov-threshold) particle detection. The combination boasts an additional handle on PID from the relative intensity of the two signals.

This detector would offer excellent energy resolution for high-energy neutrino interactions (better than 10% neutrino energy resolution achieved with preliminary algorithms), along with access to a rich program of low-energy, rare-event, and precision physics.

This is likely a cost-effective option, particularly of those designed to broaden the physics program, thanks to the relatively simple and well-understood detector design, without the need for a cryostat or field cage.

A conceptial view of the detector is shown in Fig. 15.

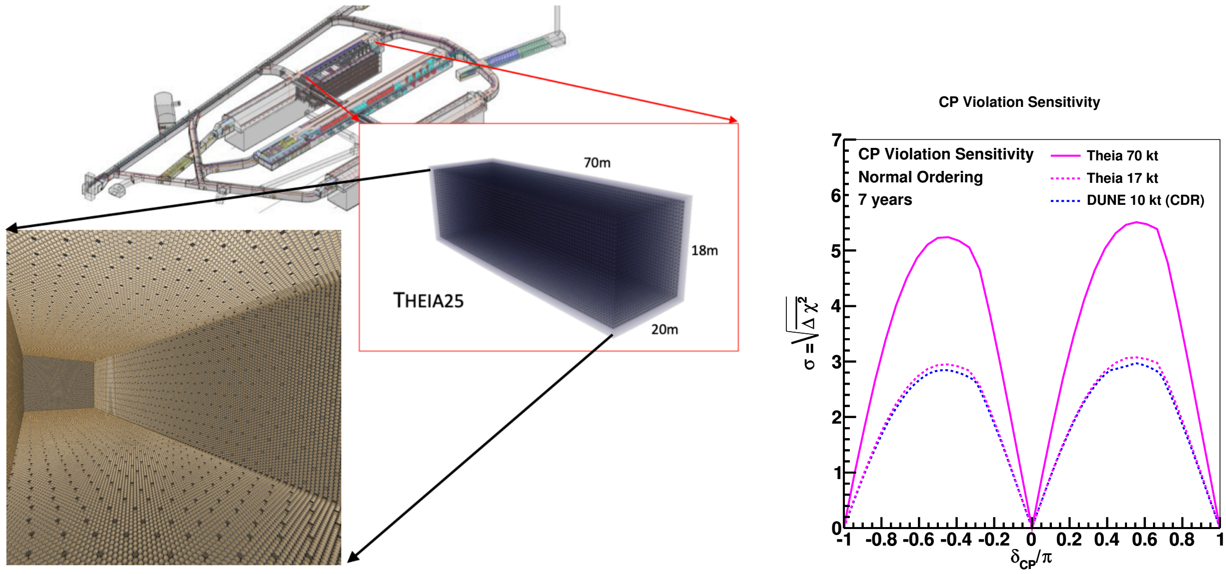

Figure 15: *Left panel:* THEIA-25 sited in the planned fourth DUNE cavern, with an interior view of THEIA-25 modeled using the Chroma optical simulation package [?]. Taken from [?]. *Right panel:* Sensitivity to CP violation (i.e.: determination that $\delta_{CP} \neq 0$ or π) as a function of the true 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) THEIA-25 WCD detector (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 [?].

CPV sensitivity Deployment of THEIA at LBNF would offer excellent sensitivity to neutrino oscillation parameters, including CP violation. Advances in Cherenkov ring imaging techniques lead to improved particle identification and ring counting, which greatly improves background rejection. The fiTQun event reconstruction package, fully implemented in the most recent T2K analyses [?], was used for THEIA sensitivity studies. Improvements include a Boosted Decision Tree. Full details can be found in [?]. Sensitivity to neutrino oscillation is enhanced by:

1. Improved particle identification using boosted decision trees removes 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. Improved electron/muon particle identification allows for an additional sample of 1-ring, one-Michel-electron events from ν_e-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.

The sensitivity to long-baseline physics at THEIA is seen to be comparable to the sensitivity of an equivalently-sized DUNE module [?, ?, ?], as shown in Fig. 15. 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 cross-check of the extracted oscillation parameter values.

add something on ND? Commment on work supported by BNL LDRD, syst uncertainties etc (concerns called out earlier re LAr ND and non-LAr FD) – unless it is covered earlier? Mike to update.

Broad physics program THEIA, named for the Titan Goddess of light, seeks to make world-leading measurements over as broad range of neutrino physics and astrophysics as possible. The scientific program would include observations of low- and high-energy solar neutrinos, determination of neutrino mass ordering and measurement of the neutrino CP-violating phase δ, observations of diffuse supernova neutrinos and neutrinos from a supernova burst, sensitive searches for nucleon decay and, ultimately, a search for neutrinoless double beta decay (NLDBD), with sensitivity reaching the normal ordering regime of neutrino mass phase space.

Table 2 summarizes the physics reach of THEIA. The full description of the analysis in each case can be found in [?].

Technology Readiness Level The THEIA design makes use of a number of novel technologies to achieve successful hybrid event detection. Water-based liquid scintillator (WbLS) [?] can be used to enhance the Cherenkov signal by reducing and potentially delaying the scintillation component. The use of angular, timing, and spectral information offers discrimination between Cherenkov and scintillation light for both low- and high-energy events. The baseline design includes fast photon detectors – such as the 8" PMTs now manufactured by Hamamatsu, which have better than 500-ps transit time spread – with spectral sorting achieved via use of dichroic filters [?].

Successful separation of Cherenkov and scintillation has been demonstrated even in a standard scintillator like LAB-PPO [?] with the use of sufficiently fast photon detectors, and will be even more powerful when coupled with the WbLS and spectral sorting capabilities planned for THEIA.

Radio-purity in excess of the requirements for the THEIA low-energy program have been demonstrated by successfully operated water Cherenkov experiments (SNO) and scintillator experiments (Borexino).

Further optimization of the design could be achieved by considering deployment of LAPPDs (Large Area Picosecond Photo-Detectors) [?, ?], for improved vertex resolution, or slow scintillators [?, ?] to provide further separation of the prompt Cherenkov component from the slower scintillation. A more complete discussion of the relevant technology, including a number of prototype experiments planned or under construction, is provided in the NF10 Snowmass white paper on "Future Advances in Photon-Based Neutrino Detectors" [?].

The R&D for THEIA will be completed with the successful operation of a number of technology demonstrators currently under construction: (i) a 30-ton engineering and optics study at BNL will demonstrate the required properties and handling of the scintillator; (ii) a low-energy

Table 2: THEIA physics reach. Exposure is listed in terms of the fiducial volume assumed for each analysis. For NLDBD the target mass assumed is the mass of the candidate isotope within the fiducial volume (assumed to be housed within an inner containment vessel). Physics goals dubbed "beyond LAr" require higher radio purity, better neutron shielding, and lower energy threshold than achievable in the baseline LAr detector design. These could be addressed by use of underground argon coupled with enhanced readout technology; this would require substantial development to produce enough to fill the 25-kton module.

Primary Physics Goal	**Reach**	**Exposure (Assumptions)**	**Context wrt DUNE-LAr**
Long-baseline oscillations	$> 5\sigma$ for 30% of δ_{CP} values	524 kt-MW-yr	Complementary
Supernova burst	$< 2°$ pointing accuracy 5,000 events	25-kt detector 10 kpc	Complementary ν vs $\bar{\nu}$
DSNB	5σ discovery	125 kton-yr (5 yrs)	Beyond LAr
CNO neutrino flux	$< 10\%$	62.5 kton-yr (5 yrs) 50% fiducial vol.	Beyond LAr
Reactor neutrino detection	2000 events	100 kton-yr (5 yrs) 80% fiducial vol.	Beyond LAr
Geo neutrino detection	2650 events	100 kton-yr (5 yrs) 80% fiducial vol.	Beyond LAr
NLDBD	$T_{1/2} > 1.1 \times 10^{28}$ yr	211 ton-yr ^{130}Te	Beyond LAr
Nucleon decay $p \to \overline{\nu} K^{+}$	$T > 3.80 \times 10^{34}$ yr (90% CL)	800 kton-yr	Complementary Different modes

performance demonstrator, EOS, at LBNL [?] will demonstrate the performance capabilities of the scintillator, fast photon detectors, and spectral sorting; and (iii) a high-energy demonstration at ANNIE, at FNAL, will demonstrate GeV-scale neutrino detection using hybrid technology [?]. These detectors are all currently operational, or due to be so by summer 2024. Following results from these demonstrators (FY25), optimization of the conceptual THEIA detector design can be completed (FY26), ready for a preliminary design exercise by FY27.

3.5 FD3 and FD4 detector integration (Stefan, Michel, Sowjanya)

Sketch of complete detector solutions for FD3/FD4. Main options.

3.6 R&D Roadmap (Stefan, Michel, Sowjanya)

Critical technical elements to be tested during R&D. Staged prototyping at CERN Neutrino Platform and elsewhere. Based on input Mary has gathered for P5.

KLOE detector at INFN-Laboratori Nazionali di Frascati and will be refurbished for Phase I, without the need for upgrades during Phase II. The Tracker, based on Straw Tubes, will be a completely new detector capable of reconstructing charged particle tracks in the magnetic field and studying neutrino cross sections on Carbon and Hydrogen targets. Major upgrades for Phase II are not foreseen.

GRAIN is an innovative LAr detector as it will employ a completely new readout technique, utilizing only scintillation light for track reconstruction. This task is accomplished by cameras with light sensors made of a matrix of Silicon Photomultipliers (SiPMs) and optical elements such as special lenses or Coded Aperture Masks. The GRAIN project is very challenging because, due to the low efficiency of light sensor to VUV scintillation light, the number if photons detected and used by the reconstruction algorithms is low. We will try for the phase II to improve light collection by improving the Photon Detection Efficiency (PDE). For this purpose, we are developing with “Fondazione Bruno Kessler” (FBK-Trento) Backside Illuminated SiPMs (BSI SiPM). In this architecture the light entrance window is on the back of the Silicon while all of metallic contacts are on the front side. This will allow us to improve the fill factor and optimize the anti reflective coating on the entrance window. We plan to substitute all the Matrices of traditional Front Side SiPMs with the new ones, if they will be available and mature for the Phase II.

4.4 Near Detector Options for Non-Argon Far Detectors

In the event that one of the Phase 2 far detectors consists of a neutrino target material that is not argon-based, such as the Theia detector concept described in Section 3.4.2, the Phase 2 near detector complex will need to provide measurements of neutrino interactions on non-argon target nuclei. Several options exist for modifying the Phase 1 suite of near detectors to make such measurements, including modifying an existing Phase 1 detector (SAND) to incorporate C, O, and H nuclear targets, embedding Water-based Liquid Scintillator (WbLS) targets within the ECAL of the Phase 2 gaseous argon TPC (GArTPC), and constructing a new, dedicated, water-based near detector.

4.4.1 Installing C/O/H Targets in SAND

(R. Petti)

4.4.2 Adding WbLS Targets to GArTPC

The GArTPC described in Section 4.1 is capable of supporting active WbLS targets within the downstream portion of the upstream ECAL, as shown in Figure 21. The WbLS layers would consist of horizontal and vertical bars (similar to the NOνA configuration discussed in the next section), and interactions in the WbLS layers produce particles that enter the high pressure gas TPC where they are precisely tracked. Neutral particles are measured by the surrounding ECAL, and the active WbLS layers provide an additional measure of low energy particles near the interaction vertex (“vertex activity”).

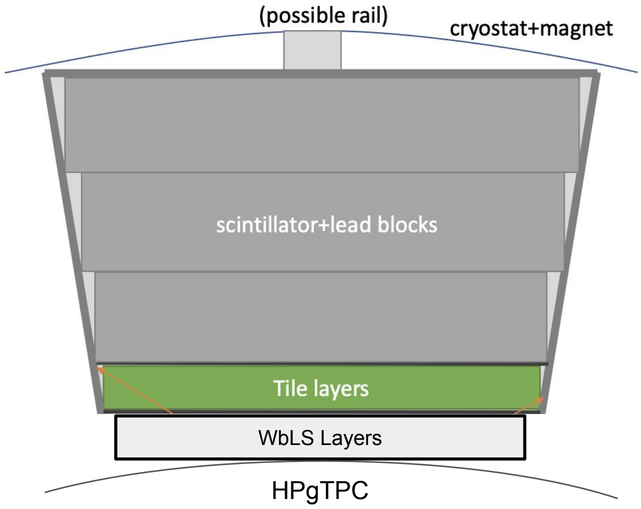

Figure 21: GArTPC w/ WbLS

There is sufficient room for WbLS layers with a thickness of at least 10 cm, which would provide more than a ton of target mass. This would produce O(1M) charged current ν_μ interactions in a 14 week run on-axis, and O(10k) charged current ν_μ interactions in a 2 week run at the furthest off-axis position, both of which would be expected to occur within a nominal DUNE yearly run.

4.4.3 Dedicated Water-based Near Detectors

It is possible to install a detector specifically designed to make measurements for a water-based far detector in the DUNE near detector hall. If a new GArTPC is built, it will serve as the downstream spectrometer for ND-LAr, allowing TMS to be used as a downstream spectrometer for a dedicated Water-based Near Detector (WbND). There is space within the existing near detector hall to add 2 new detectors (GArTPC and WbND), although this would limit the off-axis travel capabilities of the detectors within the hall; this would only be possible if sufficient off-axis data were collected with DUNE Phase 1. Another option is to excavate a small, additional section of the cavern just past the on-axis detector position to produce a new alcove (or "garage") to house the additional detectors. The PRISM rail system within the near detector hall would allow these detectors to move on-axis while ND-LAr and GArTPC are in an off-axis position. Finally, it is possible to extend the long dimension of the near detector hall to produce additional off-axis travel space that could be used to perform off-axis measurements with WbND for a fraction of the cost of the associated far detector.

NOνA-style Near Detector The NOνA near detector consists of individual cells, as shown in Figure 22, arranged in horizontal and vertical layers. The cells consist of PVC extrusions filled with liquid scintillator, and a wavelength shifting fiber collects the light and guides it to the readout avalanche photodiode (APD) [53].

The NOνA near detector design could be used to construct a WbND by replacing the

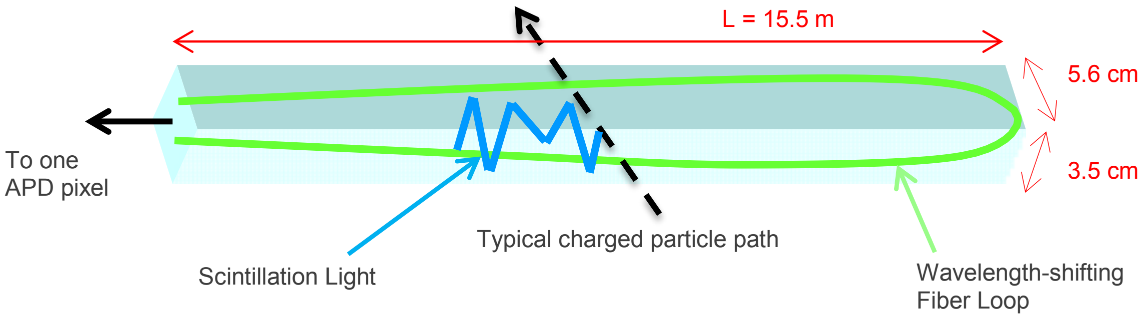

Figure 22: The fundamental unit cell of the detector of the NOνA near detector is shown. The cells are arranged in horizontal and vertical layers.

NOνA scintillator with WbLS. The cell size and scintillator fraction of the WbLS would have to be tuned to ensure a high muon reconstruction efficiency. This type of detector would also be capable of a calorimetric measurement of the hadronic energy in the neutrino final state, including better sensitivity to neutrons than a LAr detector, due to the presence of free hydrogen in the target material. This detector technology is well established and would require minimal additional R&D.

LiquidO Near Detector (A. Weber, J. Hartnell)

4.5 R&D and Engineering Road Map

R&D will be necessary for the Phase II Near detector, starting in 2024 and lasting for several years. It will be important to aim to fully define the detector requirements and have a conceptual design report in the late 2020s to be ready for construction in mid-2030s.

Some of the essential R&D and design work needed for the phase II near detector includes:

TPC charge readout and electronics test stands Charge readout TPCs are a mature technology with gas mixes identified that give sufficient gain. However, we must ensure that the full chain from amplification technology to readout electronics is tested in a high-pressure test stand to ensure adequate stability and gain in a non-flammable gas with a high argon fraction. Also, in choosing the gas, amplification technology, and readout electronics, the physics requirements need to be taken into account. With the right gas and amplification technology, the TPC can achieve a low energy threshold and get more detailed imaging of the hadronic activity at the neutrino interaction vertex. Additionally, the choice of the channel count in the readout electronics and the pixelization of the charge readout pads/strips play a role in the TPCs ability to lower the tracking threshold and achieve sub-mm point resolution.

Current testing has used wire chambers as the amplification stage, but with modern TPCs such as those for ALICE and sPHENIX using gas electron multipliers (GEMs) to achieve better stability of operation and higher gains we must also test this option. This work is ongoing in the UK (GEM work and readout electronics) and USA (readout