DUNE: Status and Perspectives

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The Deep Underground Neutrino Experiment (DUNE) provides a rich science program with a focus on neutrino oscillations and other beyond the standard model physics. The high-intensity, wide-band neutrino beam will be produced at the Fermi National Accelerator Laboratory (FNAL) and will be directed to the 40 kt liquid argon far detector at the Sanford Underground Research Facility, 1300 km from FNAL. The primary goals of the experiment are to determine the ordering of neutrino masses and to measure the CP violating phase, $\delta_{\rm CP}$. The underground location of the large DUNE far detector and its excellent energy and spatial resolution will allow also for non-accelerator physics programs predicted by grand unified theories, such as nucleon decay or $n-\bar{n}$ oscillations. Moreover, DUNE will be sensitive to the electron neutrino flux from a core-collapse supernova, providing valuable information on the phenomenon's underlying mechanisms. This ambitious project requires extensive prototyping and a testing program to guarantee that all parts of the technology are fully understood and well tested. Two such prototypes, in both single phase (ProtoDUNE-SP) and dual phase (ProtoDUNE-DP) technologies, are under construction and will be operated at the CERN Neutrino Platform (NP) starting in 2018.

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1 Introduction

The past century has seen a revolution in neutrino physics, with neutrino oscillations first confirmed within the past 20 years [1, 2, 3] now firmly entering the precision era. Neutrino oscillations rely on flavour mixing in which the three neutrino flavours are a linear combination of the three neutrino mass states, which are combined via a 3×3 mixing matrix. The matrix is typically parameterised in terms of three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and a Charge Parity (CP) violating phase δ_{CP} . Additionally, the neutrino oscillation phenomenon does not depend on the absolute mass scale but rather the neutrino mass squared difference $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.

While many experiments have pushed forward our understanding of the universe by studying neutrino oscillations, some key open questions need to be addressed by future Long BaseLine (LBL) oscillation experiments. Furthermore, a Far Detector (FD) in an LBL experiment (large active mass in a low background environment) is well suited to address certain key questions beyond neutrino physics. A broad cross section of these questions is:

- Charge Parity Violation (CPV) in neutrino oscillations δ_{CP} is yet to be measured. A CP non-conversing value of δ_{CP} ($\delta_{\text{CP}} \neq 0, \pi$) would be the first observation of CPV in the lepton sector; a requirement for leptogenesis. In some models, δ_{CP} can directly explain the matter-antimatter asymmetry [4].
- The neutrino Mass Ordering (MO) Previous experiments have only measured the magnitude of Δm_{23}^2 therefore it is not known whether the third mass state, ν_3 , is much heavier or much lighter than $\nu_{1,2}$. These scenarios are respectively known as the Normal Mass Ordering (NMO) and the Inverted Mass Ordering (IMO).
- The octant of θ_{23} Previous experiments have measured degenerate values of θ_{23} that are consistent with maximal mixing ($\theta_{23} = 45^{\circ}$). Such maximal mixing may indicate an underlying symmetry of nature.
- Grand Unified Theories (GUT) GUTs predict baryon number violating processes which are yet to be observed such as proton decay.
- Core-collapse supernova What are the underlying mechanisms and how to neutrinos play a role?

2 The Deep Underground Neutrino Experiment

The Deep Underground Neutrino Experiment (DUNE) [5, 6, 7, 8] is a future 1300 km LBL neutrino oscillation experiment, to be situated across two sites in North America

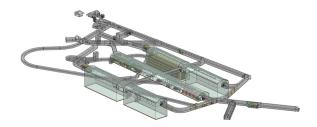


Figure 1: Schematic of the FD complex located on the 4850 level at SURF.

and aiming to address the key open questions outlined in section 1. The near site, located at the Fermi National Accelerator Laboratory (FNAL) (IL), will house the the Long Baseline Neutrino Facility (LBNF) neutrino beam and Near Detector (ND) complex. At the opposing end of the baseline, the far site in the Sanford Underground Research Facility (SURF) (SD) will house four 10 kt Liquid Argon Time Projection Chambers (LArTPCs) acting as FDs.

LBNF [7] will provide a GeV-scale, wide-band, highly pure ν_{μ} beam with an initial power of 1.2 MW, upgradeable to 2.4 MW. Based on features of the NuMI neutrino beam [9] at FNAL, the target and horn system has been tuned via a genetic algorithm to maximise sensitivity to CPV. The beam is capable of operating in Forward Horn Current (FHC) and Reverse Horn Current (RHC) modes which preferentially selects ν or $\bar{\nu}$ via reversal of the magnetic field in the focusing horns.

The role of the ND is to constrain the unoscillated neutrino interaction rate in the FD, reducing systematic uncertainties in the neutrino oscillation measurements. The ND will also provide a rich neutrino interaction cross-section measurement program. The ND, which will be housed 574 m from the LBNF target and \sim 60 m underground, will be a composite system and is under design, consisting of a LArTPC along with a Gaseous Argon (GAr) time projection chamber or a fine-grained straw tube tracker.

The FD complex, located 4850 ft underground at SURF and shown in Fig. 1, will house four 10 kt LArTPCs [8]. Two technologies are available for the FD modules; a reference design using Single Phase (SP) technology and an alternative Dual Phase (DP) design. The SP design consists of four horizontal drift regions per FD module flanked by opposing anodes and cathodes which maintain a 500 V/cm electric field. The anode is instrumented for ionisation electron readout and consists of three planes of wires. Conversely, the DP design consists of a single, vertical drift volume per FD module with a cathode on the module floor and an instrumented anode on the ceiling, maintaining a 500 V/cm electric field. Sandwiched between the Liquid Argon (LAr) surface and the anode is a GAr phase. The ionisation electrons are extracted from the LAr phase into the GAr phase and amplified by large electron multipliers. The amplified signal is then readout by the 2D segmented anode.

A staged FD installation approach will be adopted allowing an early physics program. The FD cavern groundbreaking occurred in 2017 with installation of the first

Year	Number of installed FD modules	Total mass of installed FD modules (kt)	LBNF beam power (MW)	Exposure at year end (kt MW yr)
1	2	20	1.07	21
2	3	30	1.07	54
4	4	40	1.07	128
7	4	40	1.07	300
10	4	40	2.14	556

Table 1: DUNE staged data-taking scenario. The scenario assumes a 50:50 time split between FHC and RHC LBNF beam running modes.

FD module planned for 2021. First data is expected in 2024 followed by LBNF neutrino beam and ND availability in 2026. The technology used for each FD module is dependent upon the success of the ProtoDUNE program (see section 4) but both technologies are expected to be utilised.

3 Physics reach

CPV and the neutrino MO introduce an asymmetry between the neutrino and antineutrino oscillation probabilities which causes a measurement degeneracy. The magnitude of the MO-induced asymmetry increase with baseline length whereas the CPV-induced asymmetry is constant [10]. This degeneracy can be resolved for baselines longer than 1200 km which implies that DUNE, with a 1300 km baseline, can unambiguously determine the MO and measure $\delta_{\rm CP}$.

The primary neutrino oscillation physics program of DUNE relies not only on measuring the oscillated energy spectrum of multiple samples of neutrino interactions in the FD but also measuring subtle differences between them. To establish the physics reach of DUNE prior to data-taking, a parameterised Monte Carlo (MC) simulation of the LBL physics program with GLoBES [11, 12] has been used to explore the key sensitivities of the experiment. This exploration is based on a staged construction scenario which assumes a 50:50 time split between FHC and RHC LBNF beam running and is summarised in table 1.

The parameterised MC (the Fast Monte Carlo simulation [5]) outputs selected Charged Current (CC) reconstructed spectra which are shown in Fig. 2 with applied oscillations using the NuFit 2016 [13] parameters. Each distribution shows what level of statistics would be expected after 3.5 years of data-taking in separate FHC and RHC LBNF beam running modes (seven years total).

The sensitivities to both lepton sector CPV and the neutrino MO are obtained from a fit to all four oscillated neutrino samples detailed in Fig. 2. The significance

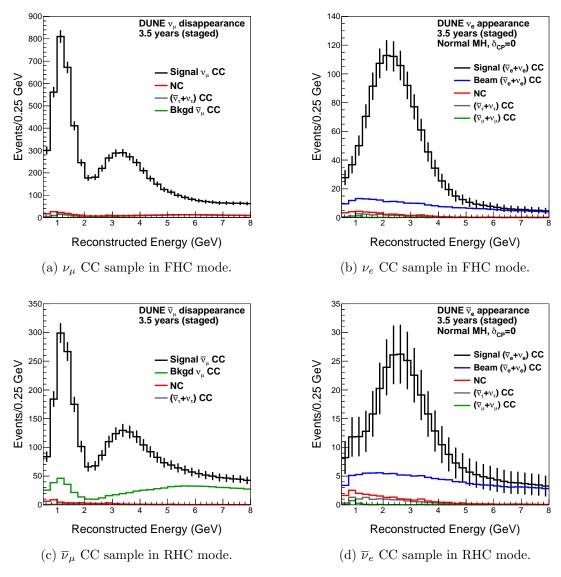
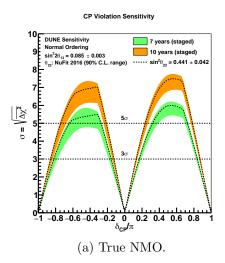


Figure 2: Reconstructed spectra of selected (anti-)neutrino CC interactions showing signal (black), Neutral Current (NC) (red), ν_{τ} and $\overline{\nu}_{\tau}$ (grey), ν_{μ} or $\overline{\nu}_{\mu}$ (green) and LBNF beam intrinsic ν_e and $\overline{\nu}_e$ (blue) interactions. Each distribution assumes a 3.5 year exposure, assuming the staging scenario described in table 1. The neutrino oscillation parameters are based on NuFit 2016 [13] with $\delta_{\rm CP}=0$ and true NMO.



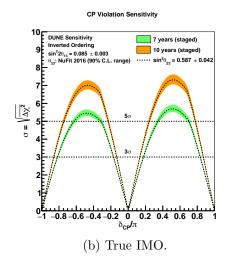


Figure 3: The significance with which $\delta_{\rm CP} \neq 0, \pi$, can be determined as a function of the true value of $\delta_{\rm CP}$, for exposures of seven (green) or 10 (orange) years, assuming the staging scenario described in table 1. The inputs to the sensitivities are shown in Fig. 2. The neutrino oscillation parameters are based on NuFit 2016 [13]. The dashed line is the sensitivity for the NuFit 2016 central value of θ_{23} with the width of the band representing the range of sensitivities for the 90% C.L. range of θ_{23} values.

with which DUNE can observe lepton sector CPV ($\delta_{\rm CP} \neq 0, \pi$) is shown in Fig. 3 as a function of the true value of $\delta_{\rm CP}$ for true NMO and IMO. Partial 5σ coverage occurs after seven years of data-taking with the coverage dramatically increasing as exposure increases to 10 years.

The significance with which DUNE can determine the neutrino MO as a function of the true value of $\delta_{\rm CP}$ is shown in Fig. 4 for both true NMO and IMO. Driven by the 1300 km baseline, Fig. 4 shows greater than 5σ sensitivity to the neutrino MO for all possible values of $\delta_{\rm CP}$.

Unlike CPV and the neutrino MO, establishing the octant of θ_{23} relies only a combined measurement of the $\nu_{\mu} \to \nu_{\mu}$ (which is sensitive to $\sin^2 2\theta_{23}$) and $\nu_{\mu} \to \nu_{e}$ (which is sensitive to $\sin^2 \theta_{23}$) oscillation channels. The significance with which DUNE can establish the octant of θ_{23} as a function of the true value of $\sin^2 \theta_{23}$ is shown in Fig. 5. Approximately 50% of the NuFit 2016 $\sin^2 \theta_{23}$ C.L. region is covered with 5σ signifiance after 10 years of data-taking.

The scope of DUNE extends into other Beyond the Standard Model (BSM) physics. GUTs predict proton lifetimes possibly within reach of the full DUNE experiment. The $p \to K^+ \overline{\nu}$ decay channel is uniquely suited to a LArTPC due to the high ionization density of the decay K^+ which results in high identification efficiency.

DUNE is also sensitive to $n - \overline{n}$ oscillations in which a nucleus-bound neutron

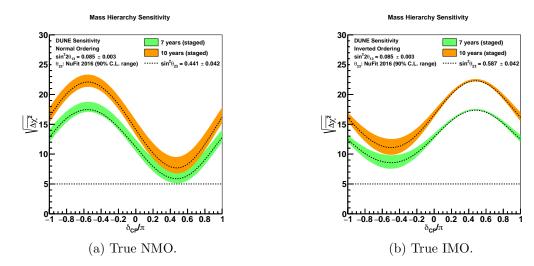


Figure 4: The significance with which the neutrino MO can be determined as a function of the true value of δ_{CP} , for exposures of seven (green) or 10 (orange) years, assuming the staging scenario described in table 1. The inputs to the sensitivities are shown in Fig. 2. The neutrino oscillation parameters are based on NuFit 2016 [13]. The dashed line is the sensitivity for the NuFit 2016 central value of θ_{23} with the width of the band representing the range of sensitivities for the 90% C.L. range of θ_{23} values.

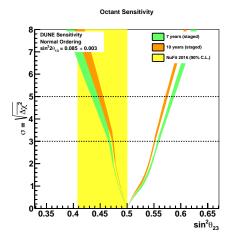


Figure 5: The significance with which the θ_{23} octant can be resolved as a function of the true value of $\sin^2\theta_{23}$, for exposures of seven (green) or 10 (orange) years, assuming the staging scenario described in table 1. The inputs to the sensitivities are shown in Fig. 2. The neutrino oscillation parameters are based on NuFit 2016 [13]. The width of the band represents the range in sensitivity due to variation in the true value of $\delta_{\rm CP}$, where the band covers the top 80% least extreme sensitivities. The yellow shaded region indicates the NuFit 2016 $\sin^2\theta_{23}$ 90% C.L. allowed region.

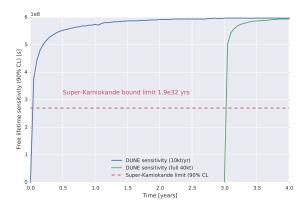


Figure 6: Free $n - \overline{n}$ lifetime sensitivity as a function of years of exposure with sensitivities for two construction scenarios (solid blue and solid green lines) and compared with the Super-K limit (orange dashed line).

converts to an anti-neutron that annihilates with another bound nucleon. This results in an isotropic burst of neutral and charged pions which resembles a distinctive star-like topology. A free lifetime sensitivity has been established using a Convolutional Neutral Network (CNN) to select this topology over the dominant atmospheric neutrino interaction background which is shown in Fig. 6.

4 ProtoDUNE

The DUNE FDs, with a combined 40 kt LAr mass, will be the largest LArTPCs ever constructed. This demands extensive R&D to establish the production process, understand subsystem integration and to validate that the design and performance is sufficient for the core physics program. To achieve this goal, two large scale prototype LArTPCs, named ProtoDUNE-SP [14] and ProtoDUNE-DP, which will use the complementary SP and DP technologies, are currently under construction at CERN and will be exposed to a GeV-scale charged particle test beam. Both prototypes will each hold 770 t of LAr and will use full scale FD components. Extensions of the H2 and H4 SPS beamlines will service ProtoDUNE-DP and ProtoDUNE-SP respectively.

The overarching aim of ProtoDUNE measurement program is acquiring a better understanding of interaction processes on argon and to optimise LArTPC reconstruction techniques. Charged pions and protons from the beam will be used to study hadronic interaction mechanisms. The electron component will be used to further develop LArTPC shower reconstruction algorithms in addition to expanding photon/electron separation techniques. Interactions from GeV-scale charged pions will produce as vast quantity of charged kaons, allowing for study of charged kaon reconstruction and identification efficiencies. Muons will provide a standard candle for

dE/dx calibration with Michel electrons from stopping muons providing a low energy benchmark for supernova neutrino interactions.

The ProtoDUNE cryostats are complete and are housed in the EHN1 building at the CERN neutrino platform. The final full-scale sub-components of the LArT-PCs are now being shipped from various construction sites in North America and Europe to CERN where installation is taking place. Commissioning and data-taking is expected to take place in 2018 prior to the SPS long shutdown.

5 Conclusions

The neutrino oscillation field is progressing rapidly but some key open questions remain. DUNE, which will utilise LArTPC technology, will be able to unambiguously determine the neutrino MO and probe lepton sector CPV in a timely manner. The extended physics program will further probe neutrino oscillations and BSM physics.

Two kt scale LArTPCs are currently under construction at CERN (the ProtoDUNE-SP and ProtoDUNE-DP prototypes) that will critically test the engineering and construction procedures of the proposed FD technologies whilst providing a rich physics program of direct use in the key measurements of DUNE.

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