DUNE Physics Program and Status

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Abstract. The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline neutrino experiment with a 70-kt liquid argon detector at the Sanford Underground Research Facility (SURF) 1300 km from Fermilab. This programme includes studies of neutrino oscillations with a high-intensity muon-neutrino beam from Fermilab; as well as, proton decay and supernova neutrino burst searches. DUNE will resolve the neutrino mass hierarchy to a precision of 5σ, for all $\delta_{\rm CP}$ values, after 2 years of running with the nominal detector design and beam configuration. It has the potential to observe charge-parity violation in the neutrino sector to a precision of 3σ (5σ) after an exposure of 5 (10) years, for 50% of all $\delta_{\rm CP}$ values. The status and schedule of the project is also presented.

1. Introduction

Neutrino oscillation experiments to date have measured five of the neutrino mixing parameters [1, 2]: the three mixing angles θ_{12} , θ_{23} , and θ_{13}, and the two squared-mass differences $\Delta{\rm m}^2_{21}$ and $|\Delta{\rm m}^2_{31}|$, where $\Delta{\rm m}^2_{ij} = {\rm m}^2_i - {\rm m}^2_j$ is the difference between the squares of the neutrino mass states in $\rm eV^2$. The neutrino mass ordering (the sign of $\Delta{\rm m}^2_{31}$) is unknown, though recent results show a weak preference for the normal ordering [3,4]. The value of $\delta_{\rm CP}$ is not well known, though neutrino oscillation data are beginning to provide some information on its value [3, 5]. The Deep Underground Neutrino Experiment (DUNE) [6] is a next-generation, long-baseline neutrino oscillation experiment which will carry out a detailed study of neutrino mixing utilizing high-intensity ν_μ and $\bar{\nu}_\mu$ beams measured over a long baseline. DUNE is designed to make significant contributions to the completion of the standard three-flavor picture by measuring the parameters governing $\nu_1-\nu_3$ and $\nu_2-\nu_3$ mixing and the neutrino mass ordering (MO) in a single experiment. Paramount among these is the search for charge-parity symmetry violation (CPV) in neutrino oscillations, potentially offering insight into the origin of the matter-antimatter asymmetry, one of the fundamental questions in particle physics and cosmology. Other primary science goals are search for proton decay and detect and measure the ν_e flux from a core-collapse supernova within our galaxy.

2. DUNE, a Long-baseline experiment

DUNE will consist of a far detector to be located about 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, USA, at a distance of 1300 km from Fermilab, where a near detector will be located. The DUNE experiment will observe neutrinos from a high-power ν_μ and $\bar{\nu}_\mu$ beam peaked at ∼2.5 GeV but with a broad range of neutrino energies (see figure 1). The intense neutrino beam provided by Long-Baseline Neutrino Facility

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(LBNF) is produced using protons from Fermilab's Main Injector with a power of 1.2 MW, upgradeable to 2.4 MW.

All these features give DUNE unique physics reach. Its broad-band beam makes it sensitive to three-flavor oscillation parameters and mass ordering in a single-experiment since several oscillation nodes are accesible, as can be seen in figure 2. The neutrino and antineutrino modes are critical to measure δ_{CP} and mass ordering. The electron neutrino appearance probability, $\mathrm{P}(\nu_\mu \to \nu_e)$, is plotted in figure 2 at a baseline of 1300 km as a function of neutrino energy for several values of δ_{CP}. As this figure illustrates, the value of δ_{CP} affects both the amplitude and phase of the oscillation. The difference in probability amplitude for different values of δ_{CP} is larger at higher oscillation nodes, which correspond to energies less than 1.5 GeV. DUNE will be capable of mapping out the spectrum of observed oscillations down to energies of 500 MeV.

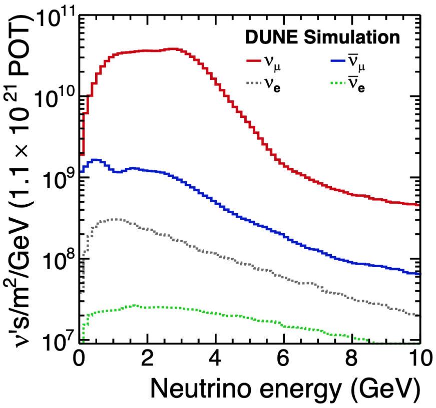

Figure 1. Un-oscillated neutrino fluxes at the far detector for neutrino mode beam running [7].

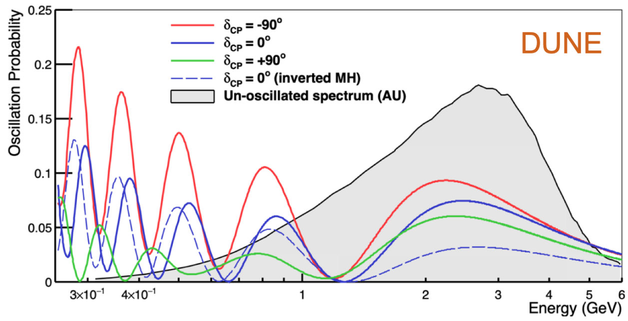

Figure 2. The appearance probability, $P(\nu_\mu \to \nu_e)$, at a baseline of 1300 km, as a function of neutrino energy for different δ_{CP} values and inverse and normal MO.

2.1. DUNE Near Detector

The high-resolution DUNE near detector (ND) [8], located in a hall 574 m from the neutrino source, will be used to characterize the neutrino beam flux and flavor composition. Comparing the measured neutrino energy spectra at the near and far sites allows us to disentangle the different energy-dependent effects that modulate the beam spectrum and to reduce the systematic uncertainties. In addition, the ND will measure neutrino-argon interactions with high precision, which will further reduce the systematic uncertainties associated with the modeling of these interactions. The ND will include three primary detector components, illustrated in figure 3

- ND-LAr consists of 35 optically separated liquid argon TPC (LArTPC) modules that allow for independent identification of $\nu-$Ar interactions in an intense beam environment. Each TPC consists of a high voltage cathode, a low profile field cage that minimize the amount of inactive material between modules, a light collection system, and a pixel based charge readout. It contains the same target nucleus and shares some aspects of form and functionality with the FD.
- ND-GAr is high-pressure gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field. It provides a lower density medium with excellent tracking resolution for muons from the ND-LAr.

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- System for on-Axis Neutrino Detection (SAND) is the beam monitor that remains on-axis at all times and serves as a dedicated neutrino spectrum monitor. It can also provide an excellent on- axis neutrino flux determination. SAND consists of an inner tracker surrounded by an ECAL inside a large solenoidal magnet.

The first two elements can move off-axis relative to the beam, providing access to different neutrino energy spectra. The movement off-axis, called DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM), exploits the fact that the peak neutrino energy decreases as the observation angle relative to the beam direction increases with narrower energy distribution. Measurements at various off-axis positions with a movable detector allow for a data-driven determination of the relationship between true and reconstructed energy that is significantly less sensitive to neutrino interaction models.

2.2. DUNE Far Detector

Finally, the DUNE far detector (FD) [9] will consist of four liquid argon time-projection chambers (LArTPC) with a total mass of nearly 70 kt (fiducial mass of at least 40 kt), installed approximately 1.5 km underground. This LAr technology will make it possible to reconstruct neutrino interactions with image-like precision. The design of the four identically sized modules is sufficiently flexible for staging construction and evolving the LArTPC technology. The first FD Module will use the single-phase (SP) technology, in which ionization charges drift horizontally in the LAr under the influence of an electric field towards a vertical anode, where they are read out. Four 3.5 m drift volumes are created between five alternating anode and cathode walls, each wall having dimensions of 58 m 12 m, and installed inside a cryostat, shown in figure 4,

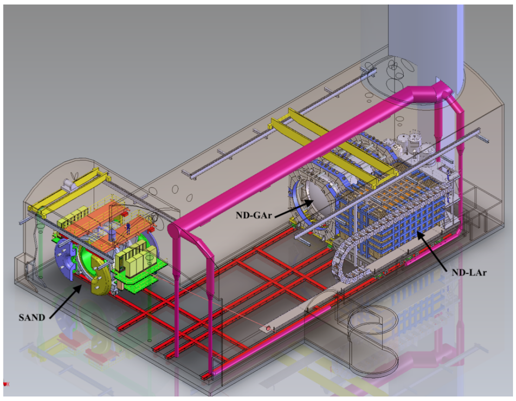

Figure 3. DUNE ND. The axis of the beam is shown as it enters from the right. Neutrinos first encounter the ND-LAr (right), the ND-GAr (center), and then the on-axis beam monitor, SAND (left).

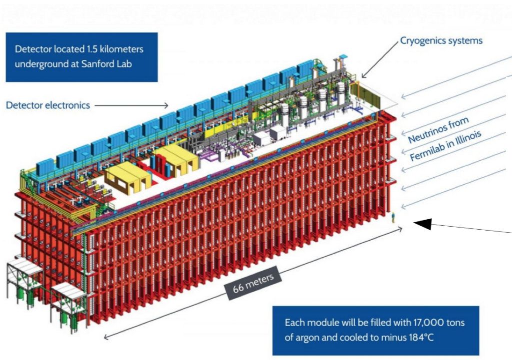

Figure 4. A 65.8m (L) by 18.9m (W) by 17.8m (H) outer-dimension cryostat that houses a 17kt FD module. A mezzanine (light blue) installed 2.3m above the cryostat supports both detector and cryogenics instrumentation.

3. Three-flavor long-baseline neutrino oscillation

In this section, selected sensitivity projections from the central elements of the DUNE science program are presented. The key strength of the DUNE design concept is its ability to robustly measure the oscillation patterns of ν_μ and $\bar{\nu}_\mu$ over a range of energies spanning the first and second oscillation maxima. This is accomplished by a coordinated analysis of the reconstructed

ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ energy spectra in near and far detectors, incorporating data collected in neutrino and antineutrino modes.

3.1. *Deployment scenario*

In this work, FD event rates are calculated assuming the following nominal deployment plan:

- Start of beam run: two FD module volumes for total fiducial mass of 20 kt, 1.2 MW beam
- After one year: add one FD module volume for total fiducial mass of 30 kt
- After three years: add one FD module volume for total fiducial mass of 40 kt
- After six years: upgrade to 2.4 MW beam

3.2. *Results from sensitivity studies*

Figure 5 shows the significance with which the neutrino mass ordering can be determined in normal ordering (NO) as a function of the true value of δ_{CP}, for both seven and ten year exposures, including the effect of all other oscillation and systematic parameters. DUNE will be able to establish the neutrino mass ordering at the 5σ level for 100% of δ_{CP} values after 2 years of running with the nominal detector design.

Figure 6 shows the significance with which CPV ($\delta_{\mathrm{CP}} \neq [0, \pm\pi]$) can be observed in NO as a function of the true value of δ_{CP}, using the staging scenario described previously. This sensitivity has a characteristic double peak structure because the significance of a CPV measurement necessarily decreases around CP-conserving values of δ_{CP}. The median CPV sensitivity reaches 5σ for a small range of values after an exposure of seven years in NO, and a broad range of values after a ten year exposure. In inverted ordering, DUNE has slightly stronger sensitivity to CPV, and reaches 5σ for a broad range of values after a seven year exposure.

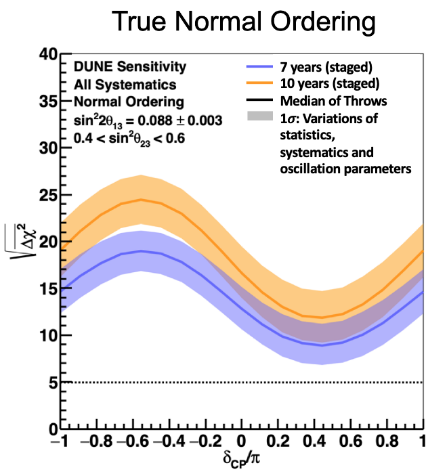

Figure 5. Significance of the determination of the neutrino mass ordering, as a function of the value of δ_{CP}, for seven (blue) and ten (orange) years of exposure. The width of the transparent bands cover 68% of fits in which random throws are used to simulate statistical and systematic variations [7].

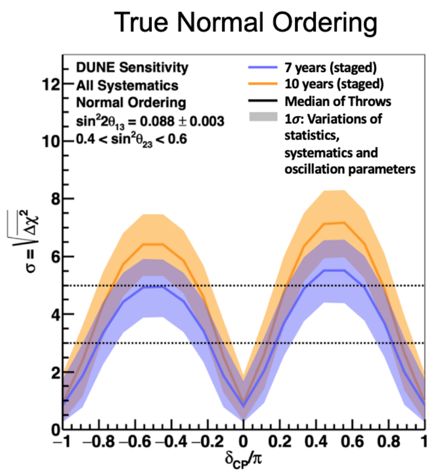

Figure 6. Significance of the DUNE determination of CPV as a function of the value of δ_{CP}, for seven (blue) and ten (orange) years of exposure.The width of the transparent bands cover 68% of fits in which random throws are used to simulate statistical and systematic variations [7].

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4. ProtoDUNE Program

The DUNE collaboration has constructed and operated two large prototype detectors, ProtoDUNE- SP and ProtoDUNE-DP, at CERN from 2018 to 2020, with the aim of validating the detector elements and measuring the physics response of the detector. Each prototype is approximately one-twentieth the size of the planned FD modules but uses components identical in size to those of the full-scale module. ProtoDUNE-SP has the same 3.5m maximum drift length as the full SP module. ProtoDUNE-DP has a 6m maximum drift length, half that planned for the DP module. Figure 7 shows the two cryostats, ProtoDUNE-SP in the foreground and ProtoDUNE-DP at an angle in the rear. ProtoDUNE-SP successful operation has demonstrated the effectiveness of the single-phase far detector design [10]. ProtoDUNE-DP has experience some issues in the high-voltage system that prevented the correct operation of the detector; a new single-phase design inspired in the dual-phase long vertical drift will be tested in 2023-2024 for the second FD module. Since the final design of the first FD module has modifications, a second run of ProtoDUNE-SP will validate the detector elements in 2022.

Figure 7. ProtoDUNE-SP and ProtoDUNE-DP cryostats in the CERN Neutrino Platform

5. Schedule and Plans

DUNE cavern excavation is ongoing and will be completed by 2024 when the installation of the first FD module will start. The neutrino beam will be available in late 20s and the FD physics data is expected in the same timescale. The DUNE ND completed its conceptual design report in 2021 and it is preparing its own prototyping; the near site preparation is also in progress.

6. Conclusions

Precise understanding of neutrino oscillation phenomena, precision measurements of the oscillation parameters and determining CP violation phase in lepton sector are among the main goals of DUNE experiment. The far site cavern construction in South Dakota has been ongoing. Two large-scalable DUNE LArTPC prototype detectors have been operated and shown excellent performance. The construction of the first FD module will start in 2024.

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