PROCEEDINGS OF SCIENCE

The DUNE Experiment

Deepika Jena on behalf of The DUNE Collaboration[a,*]

[a] *Fermi National Accelerator laboratory, USA*

E-mail: djena@fnal.gov

The Deep Underground Neutrino Experiment (DUNE) is a "next-generation" long-baseline neutrino experiment built to answer some of the most fundamental questions in the universe. DUNE will consist of two neutrino detectors placed in the world's most intense neutrino beam facility named as Long-Baseline Neutrino Facility (LBNF). It consists of a near-detector (ND) and a far-detector (FD) comprised initially of two modules and eventually of four modules, each of fiducial mass 17.5 ktons of liquid Argon. The far detector is located 1300 km from the beam source placed underground at the Sanford Underground Research Laboratory in Lead, South Dakota. The un-oscillated neutrino-nucleus interactions at near detector and oscillated interactions at far detector will be able to address the questions about the preponderance of matter over antimatter in the early universe, leptonic charge-parity symmetry violation, proton decay, supernova neutrino bursts and unification of forces. This article discusses the current status and the physics expectations in the DUNE experiment.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

*Speaker

https://pos.sissa.it/

PoS(HQL2023)023

1. Introduction

The discovery of neutrino oscillation [1–4], wherein neutrinos transition between different flavors, provides compelling evidence for both neutrino mixing and the existence of non-zero neutrino masses. Delving deeper into the characteristics of neutrinos has become a crucial objective in the realm of particle physics. The T2K experiment [5] indicated the CP-violation with 3σ confidence level for δ_{rmCP} in the lepton sector. The neutrino experiments are getting exciting, and becoming bigger in manner of both detector size and physics potential for higher precision and possibility of new physics. The DUNE is a long-baseline neutrino experiment which will be build to answer one of the fundamental questions in the understanding of our universe. The DUNE experiment will use the most intense neutrino beam and a suite of capable near and FD to study the neutrino oscillations. Figure 1. shows a schematic of the beamline and detectors at two different facilities. This will include measurements of CP-phase, mixing angles θ_{23} and the octant in which this angle lies, determining the neutrino mass ordering and sensitive tests of the three-neutrino paradigm. It will measure ν_e flux from core-collapse supernova within our galaxy which is expected once during DUNE lifetime and give information about early stages of core-collapse and birth of a black hole. DUNE will also search for proton decay in various decay modes which will provide information on grand unification of forces.

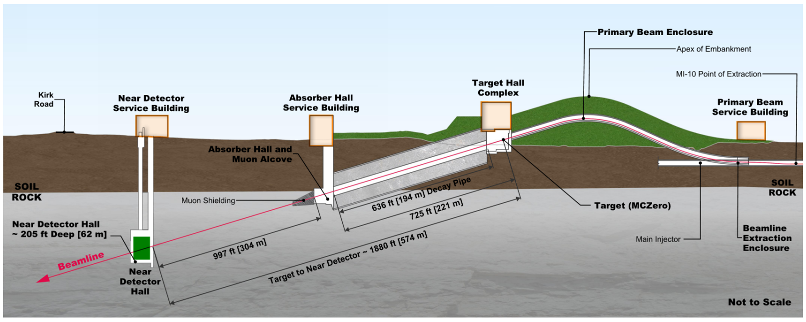

Figure 1: LBNF Beamline from Fermilab, Illinois to South Dakota [6]

2. The DUNE Experiment

The DUNE experiment will consist of a near detector located at 574 m from the neutrino source at Fermilab, Illinois and a far detector located at 1300 km away from Fermilab and about 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, USA [9]. Being close to the neutrino source, the ND will measure the initial un-oscillated muon and electron flavor neutrino nucleus interactions as well as those of the corresponding antineutrinos, whereas the FD being away from the neutrino source will measure the oscillated neutrino nucleus interactions. The oscillation probability can be measured by comparing the rate both the detectors. The rate of neutrino nucleus interaction depends on the neutrino flux and the interaction cross section and detector acceptance [8]. Figure 2. shows the expected spectrum of muon to electron neutrino flavor oscillation probability at different values of δ_{rmCP}. It is observed that due to the variation in oscillation probabilities of $\nu_\mu \to \nu_e$ with δ_{rmCP} values, it is possible to experimentally measure the

δ_{rmCP} at a fixed baseline of around 1300 km over an energy range that encompasses at least one full oscillation interval [8]. DUNE aims to measure CP violation phase by looking at muon neutrino disappearance spectra and electron neutrino appearance spectra via neutrino nucleus interaction in LARTPC at FD. Figure 3. shows the predicted rate of events for ν_e appearance and ν_μ disappearance including flux, cross-section and oscillation probabilities as a function of reconstructed neutrino energy observed at the FD. Figure 4. shows the appearance and disappearance spectrum for antineutrinos. The observed event spectrum shown in Figure 3. and 4. has assumed 3.5 years (staged) exposure for FHC and RHC for a total run time of 7 years which is estimated on an assumed deployment plan based on DUNE's technically limited schedule.

- Year 1 (Start of beam run): 1.2 MW beam and 2 FD modules for a total fiducial mass of 20 kt.
- After 1 year: Addition of one FD module for a total detector mass of 30 kt.
- After 3 years: Addition of fourth FD module for a total fiducial mass of 40 kt.
- After six years: Upgrade of beam power to 2.4 MW.

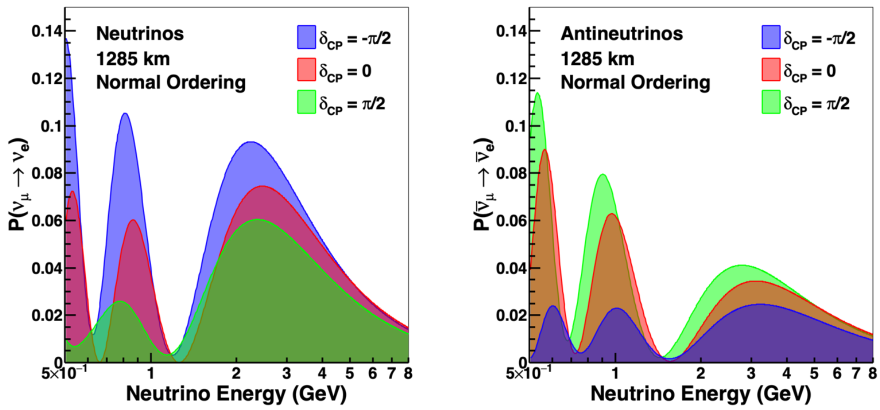

Figure 2: The appearance probability for a muon to electron neutrinos (left) and anti-neutrinos (right) as a function of neutrino energy for $\delta_{rmCP} = -\pi/2$ (purple), 0 (red) and $\pi/2$ (green) at a baseline of 1300 km for normal hierarchy [8].

In order to achieve the precision required by DUNE's goals for measuring δ_{rmCP} and determine mass ordering, the experiment must understand and minimize systematic uncertainties. Figure 5. shows the significance of the DUNE determination of CP-violation for 75% of possible true δ_{rmCP} values as a function of exposure. The plots clearly tell how well DUNE will be able to measure the δ_{rmCP} phase of the neutrino mixing matrix for different systematic scenarios. For neutrino and antineutrino mode configuration, the DUNE signal normalization uncertainty is given to be $5\% \oplus 2\%$, where 5% is the normalization uncertainty on the ν_μ FD sample and 2% uncorrelated uncertainty on ν_e sample with fit applied to both FD and ND data including all external constraints [7]. There is a big difference in terms of years between DUNE's signal systematic goal of 1% and 2% to get nearly 3σ for 75% of feasible values of δ_{rmCP}. This degree of systematic uncertainties

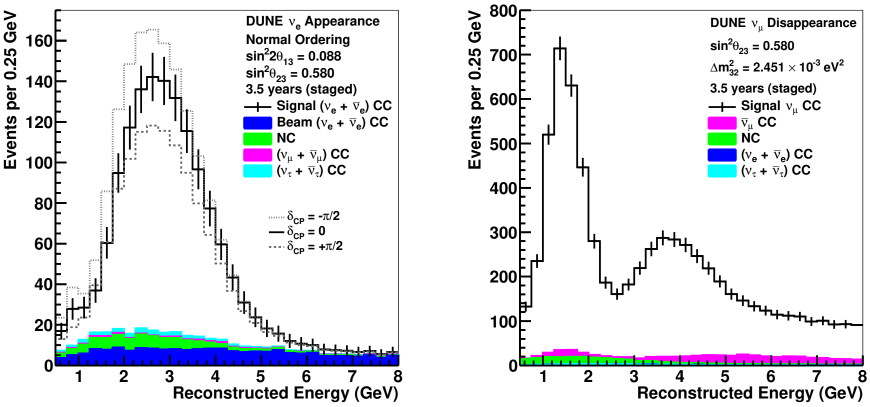

Figure 3: ν_e and ν_μ appearance and disappearance spectra: Reconstructed energy distribution of selected ν_μ CC-like events and ν_e CC-like events assuming 3.5 years (staged) running in the neutrino and anti-neutrino beam mode. The plots assumes normal ordering [8].

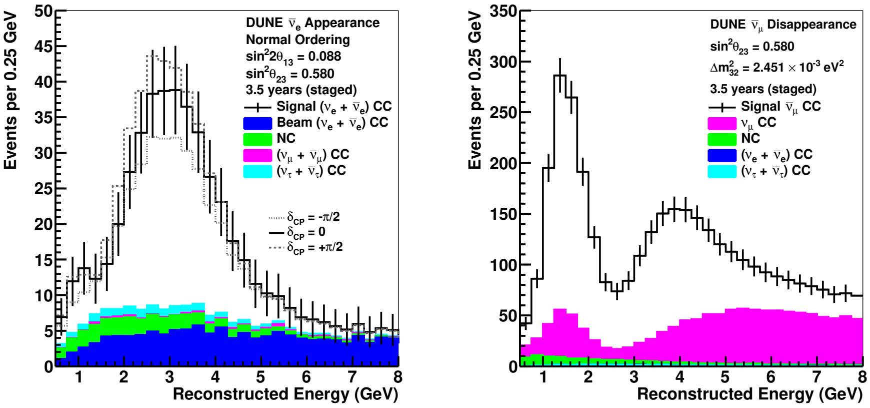

Figure 4: $\bar{\nu}_e$ and $\bar{\nu}_\mu$ appearance and disappearance spectra for assuming 3.5 years (staged) running in the anti neutrino-beam mode [8].

needed by DUNE determines the design requirement for beam as well as positioning of the near and FD.

3. DUNE Near Detector

The DUNE ND is composed of three main elements: ND-LAr, featuring a liquid argon time projection chamber; ND-GAr, housing a gaseous argon TPC detector; and SAND, designed as a magnetized beam monitor. Both ND-LAr and ND-GAr detectors are equipped to shift to off-axis beam positions, enabling them to collect data for DUNE PRISM studies [9].

The primary module in DUNE ND-LAr is the Liquid Argon Time Projection Chamber (LArTPC), constructed with ArgonCube technology. DUNE ND-LAr employs the same target nucleus and technology that will be utilized in the DUNE FD. This would help reduce the detector-

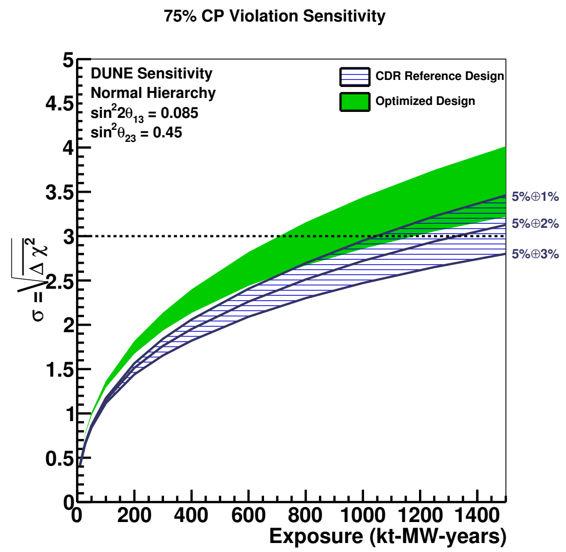

Figure 5: The expected DUNE sensitivity for the discovery of CP violation ($\delta_{CP} \neq 0, \pi$) as a function of exposure, presuming equal running in neutrino and antineutrino mode for different values for the ν_e and $\bar{\nu}_e$ signal normalization uncertainties from 5% ⊕ 3% to 5% ⊕ 1%.[7]

driven systematic uncertainties and sensitivity to nuclear effects in the extractions of the oscillation signals at the FD as well as provide information of neutrino interaction cross sections in liquid Argon. The ND-LAr is fabricated as a collection of 35 individual TPC modules, as originally designed for the ArgonCube prototype. This design of ND-Lar will enable for high statistics, small drift region and better particle identification.

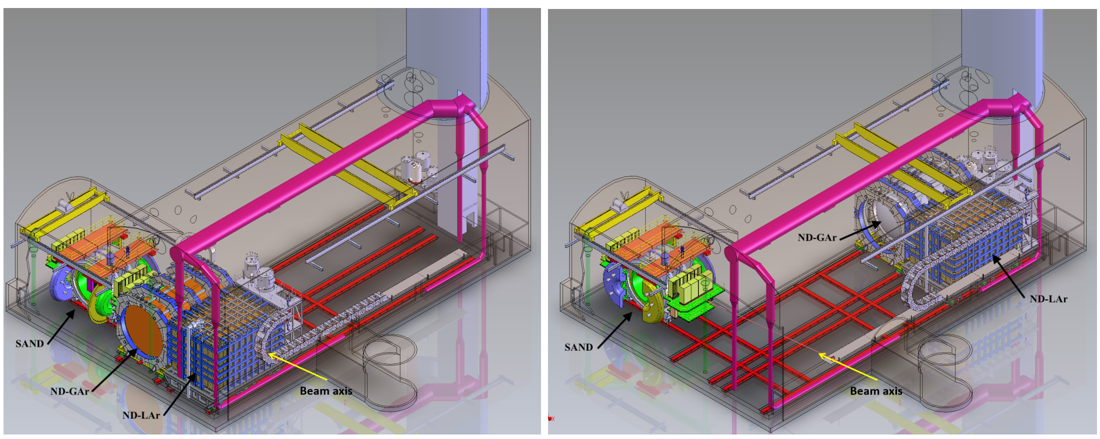

Figure 6: DUNE ND with ND-LAr and ND-GAr in the on-axis (Left) and off-axis (Right) beam positions. The SAND detector is shown in beam on-axis position.

The ND-GAr detector contains high pressure gaseous argon TPC enclosed by an electromagnetic calorimeter and further surrounded by a muon spectrometer to track muons produced in ν_μ CC interactions in the LAr-TPC. The design of the central TPC component of ND-GAr is based on the ALICE experiment at CERN. The ND-GAr detector will be capable to measure particles with low threshold and reduces multiple scattering and re-interactions of final-state particles.

The last component of DUNE ND is a magnetized beam monitor called the System for on-Axis Neutrino Detection (SAND). With its on-axis position relative to the beam, it will serve as beam monitor by measuring the neutrino spectrum. The SAND can also measure the neutrino interactions on various targets.

4. DUNE Far Detector

In Phase I, the FD will consist of two LArTPC modules, each with a fiducial mass of 17.5 kt. It is envisioned to add two more modules in phase-II to achieve a total mass of 70 kt of LAr. The use of LAr makes it an excellent choice for DUNE due to its excellent tracking capabilities, clean separation of ν_μ and ν_e charged currents, low thresholds for charged particles, precise reconstruction of lepton and hadronic energy and neutrino energy reconstruction over broad energy range.

DUNE FD plans to use two LAr detector technologies for the read out of ionization signals in the liquid argon volume which will work in Single-Phase (SP) and Dual-Phase (DP) modes. In the SP-LAr technology the ionization charges will be drifted horizontally and will be read out on wires in the liquid argon as seen in Figure 7 (Left). The maximum drift length will 3.5m and drift field is 500V/m with a cathode high voltage of 180 kV. Since no signal amplification occurs in this process, it requires low-noise electronics to achieve good signal-to-noise ratio. In the dual-phase LAr technology, the ionization charges will drift vertically in LAr and carried into gas layer above the liquid. The operating principle of dual-phase LAr technology is shown in the Figure 7 (right). This technology will allow the increase in the drift length upto 12 meter with a cathode high voltage of 600 kV.

DUNE is working on large prototypes for FD built at CERN called as ProtoDUNE. These prototype detectors are approximately one-twentieth the size of a DUNE detector module and has same principle components as that of full detector module [6]. The data collected from the DUNE-FD prototype will allow to validate the performance of the TPC designs, perform calibration and simulation with important electron, proton and kaon re-scattering data on argon target.

5. Conclusions

DUNE will be capable to make measurements of δ_{rmCP} with maximum precision and determine the mass ordering and other parameters in the mixing matrix governing the neutrino oscillations. This will complete the standard neutrino three-flavor mixing paradigm, provide insight into physics beyond the standard model and information about the origin of baryon asymmetry in universe. The large detector size with high resolution will allow for better reconstruction techniques and enable new physics measurement for groundbreaking discoveries. The LBNF beamline along with the exposure of near detector will provide an intense neutrino flux which will allow to collect high statistics data providing with a wealth of neutrino interaction measurements which is an important component of the DUNE collaboration's ancillary scientific goals.

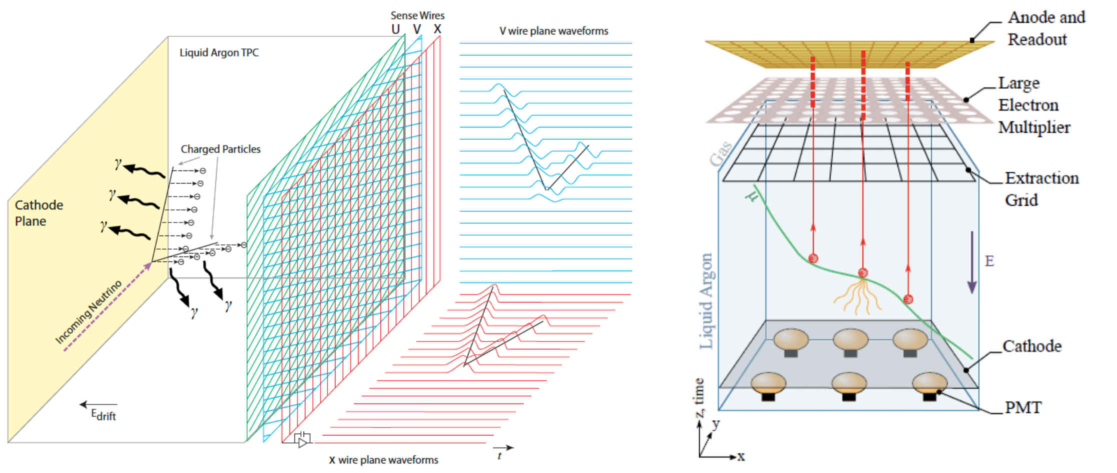

Figure 7: Operating principle of Single-Phase technology (Left) and Dual-Phase technology (Right) [6]

References

[1] Y. Fukuda *et al.* [Super-Kamiokande], Phys. Rev. Lett. **81** (1998), 1562-1567 doi:10.1103/PhysRevLett.81.1562 [arXiv:hep-ex/9807003 [hep-ex]].

[2] Q. R. Ahmad *et al.* [SNO], Phys. Rev. Lett. **87** (2001), 071301 doi:10.1103/PhysRevLett.87.071301 [arXiv:nucl-ex/0106015 [nucl-ex]].

[3] K. S. Hirata *et al.* [Kamiokande-II], Phys. Lett. B **205** (1988), 416 doi:10.1016/0370-2693(88)91690-5

[4] Y. Fukuda *et al.* [Super-Kamiokande], Phys. Lett. B **433** (1998), 9-18 doi:10.1016/S0370-2693(98)00476-6 [arXiv:hep-ex/9803006 [hep-ex]].

[5] K. Abe *et al.* [T2K], "Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations," Nature **580**, no.7803, 339-344 (2020) [erratum: Nature **583**, no.7814, E16 (2020)] doi:10.1038/s41586-020-2177-0 [arXiv:1910.03887 [hep-ex]].

[6] B. Abi *et al.* [DUNE], "Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics," [arXiv:2002.03005 [hep-ex]].

[7] R. Acciarri *et al.* [DUNE], "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF," [arXiv:1512.06148 [physics.ins-det]].

[8] B. Abi *et al.* [DUNE], "Long-baseline neutrino oscillation physics potential of the DUNE experiment," Eur. Phys. J. C **80**, no.10, 978 (2020) doi:10.1140/epjc/s10052-020-08456-z [arXiv:2006.16043 [hep-ex]].

[9] V. Hewes *et al.* [DUNE], "Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report," Instruments **5**, no.4, 31 (2021) doi:10.3390/instruments5040031 [arXiv:2103.13910 [physics.ins-det]].

[10] B. Abi *et al.* [DUNE], "Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I Introduction to DUNE," JINST **15**, no.08, T08008 (2020) doi:10.1088/1748-0221/15/08/T08008 [arXiv:2002.02967 [physics.ins-det]].