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Status of the DUNE experiment

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The Deep Underground Neutrino Experiment aims at an unprecedentedly precise neutrino CP violation phase measurement with a broad-band $\nu_\mu/\bar{\nu}_\mu$ beam, a 1,300 km baseline, an order of 10s kt fiducial mass detector with high particle identification efficiency and low external background. Additionally, the orders of systematic uncertainty should be constrained to 2% for the signal and 5% for the background. This uncertainty constraint requires an unprecedented level of robustness and redundancy in the near detector measurement. In this presentation, the near detector design and the far detector prototyping status are shown. The long-baseline sensitivity and different physics potentials are described.

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1. Introduction

The neutrino oscillation phenomenon has been measured for decades. Many facts have been learned with the past experiments. The neutrino interacts in the flavor state and propagates in the mass state. The neutrino mixing between those two states can be described by the PMNS matrix (Pontecorvo–Maki–Nakagawa–Sakata matrix). Assuming the neutrinos are Dirac particles, there are three mixing angles and one CP-violation phase (δ_{CP}) in the PMNS matrix. The three mixing angles are measured to be non-zero to date at a high confidence level. Remarkably, the mixing angle θ_{13} is measured to be non-zero with reactor experiments such as Double Chooz [1], Daya Bay [2] and RENO [3] experiments. Such a non-zero θ_{13} induces a popular topic of measuring the CP-violation phase, which represents the strength of the asymmetry of the neutrino and antineutrino oscillation.

The measurement of δ_{CP} requires a neutrino/antineutrino beam, a massive detector with a long baseline to the beam source, and unprecedented systematic uncertainty control. The Deep Underground Neutrino Experiment (DUNE) was proposed to measure the δ_{CP} with unprecedented precision. In addition, due to the unique experimental design, DUNE can solve the mass hierarchy and θ_{23} octant degeneracy problems at once [4].

There are several operating experiments making an effort to measure δ_{CP}. The leading experiments are Tokai-To-Kamioka (T2K) and NuMI Off-axis Neutrino Appearance (NOvA) projects [5] [6]. In the DUNE era, they may have decent measurements of δ_{CP}. However, compared to T2K and NOvA, an exceptional feature of DUNE is its broad-band beam. Such a beam allows utilizing more than one oscillation maximum in the neutrino spectrum, which leads DUNE to reach an unprecedented precision. In the following sections, an overview of DUNE, the design of the near detector and far detector, the long-baseline sensitivity, and physics potential beyond the long-baseline oscillation measurement are presented.

2. Deep Underground Neutrino Experiment

The DUNE collaboration has more than 1,300 collaborators from more than 200 institutes in 33 countries and CERN. It is worth mentioning that there are many parallel presentations in NuFact2021. DUNE plans to operate a powerful neutrino beam source at Fermilab, IL. The beamline can operate in the Forward Horn Current (FHC) or Reverse Horn Current (RHC) modes, which delivers ν_μ and $\bar{\nu}_\mu$, respectively. A near detector (ND) complex is located at Fermilab with a distance of 574 m from the beam source, while a far detector (FD) complex is located at Sanford Underground Research Facility (SURF), SD, 1,300 km away from the beam source. The near detector measures the un-oscillated neutrino and antineutrino spectra and provides systematic uncertainty constraints. The far detector measures the oscillated neutrino and antineutrino spectra. The oscillation parameters can be extracted by combining the measurements in both near and far detectors. Fig. 1 shows an overview of the DUNE experiment. The neutrino/antineutrino beam is delivered from the right to the left.

DUNE uses a broad-band neutrino beam energy ranging from sub-GeV to a few GeV. The Proton Improvement Plan II (PIP-II), an enhancement to the Fermilab accelerator complex, powering the world's most intense high-energy neutrino beam, has been implemented. It brings a 1.2 MW neutrino beam upgradable to 2.4 MW. The beam optimization is completed by scanning different horn and target geometries to identify those that produced the optimal sensitivity to the CP violation phase. Fig. 2 shows flux spectra of the FHC (left) and RHC (right) modes.

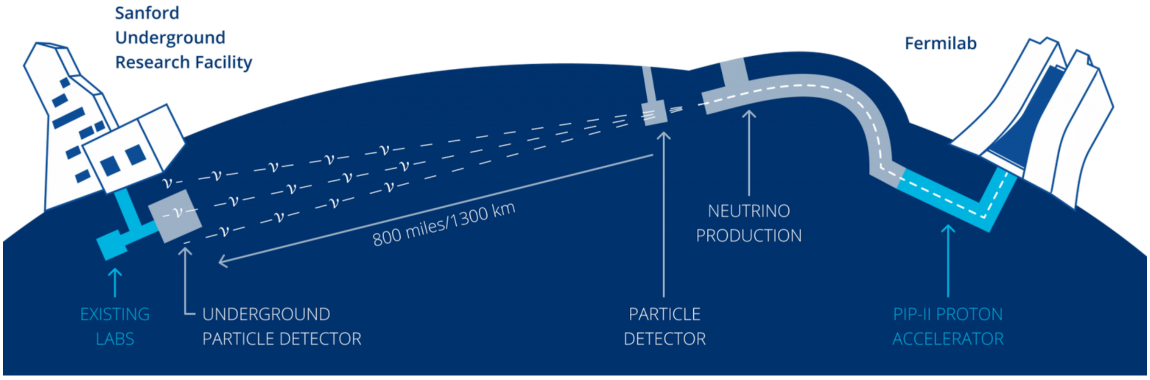

Figure 1: The overview of the DUNE experiment.

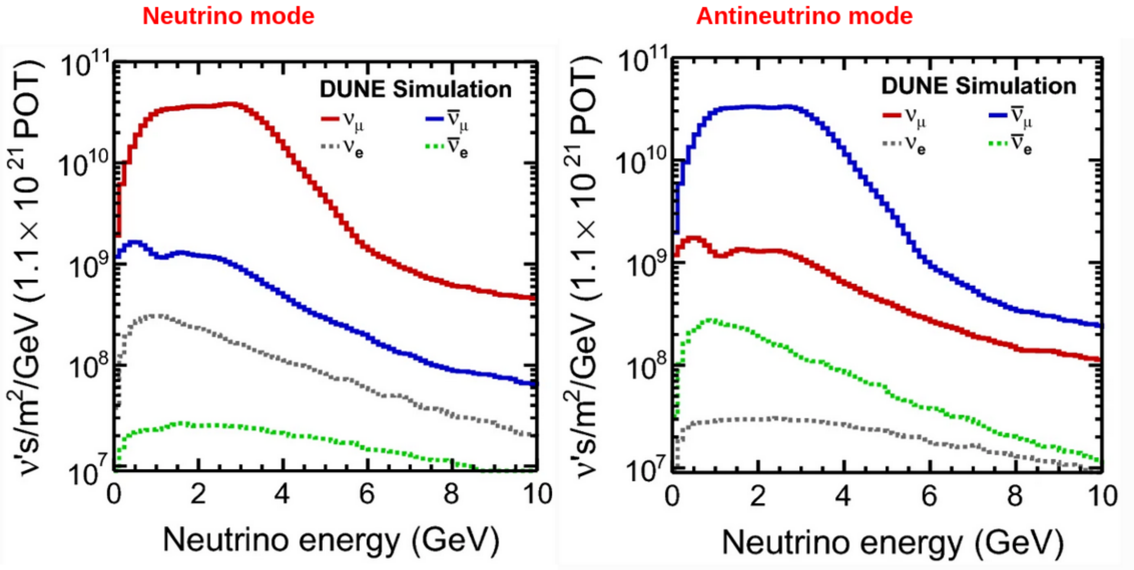

Figure 2: The neutrino flux with FHC (left) and RHC (right). Figure is taken from [19].

3. DUNE near detector

The main goal of the ND is to constrain the cross-section, beam flux, and energy response independently as well as possible. Since the flux measurement is target material independent, various detector systems and interaction channels can be used to constrain the flux. Furthermore, the ND is supposed to better measure the neutrino interaction than the FD to provide additional interaction model constraints. Such measurement requires the ND to have the same target material but better phase space coverage, particle identification, and energy reconstruction. In order to provide constraint of the FD detection systematic uncertainty, the ND is designed to be capable of measuring events in a similar way to the FD, i.e., similar technology. In summary, a hybrid detector is proposed with three components: a liquid argon TPC (ND-LAr), a gaseous argon TPC (ND-GAr), and an on-axis neutrino spectrometer (SAND). A conceptual design report of the ND has been published in [7].

In addition, DUNE plans to make the ND-LAr and ND-GAr movable continuously along the transverse direction to the neutrino beam. The peak energy of the on-axis beam is about 2.4 GeV. The peak energy is narrower and smaller when the detector goes more and more off-axis. For example, at the location 30 m off-axis, the neutrino energy peak is reduced to about 500 MeV. Continuously moving the detector off-axis enables many samplings of different neutrino fluxes. By linearly combining the sampled fluxes, desired beam fluxes can be obtained. Those artificial flux samples provide a new angle to look at the neutrino interaction channels. For example, this sampling offers a direct way of extrapolating near detector measurements to the far detector, thus reducing the model dependence on the neutrino interaction cross-section. This concept is called DUNEPRISM. The ND-LAr and ND-GAr will operate with the DUNEPRISM concept, and the SAND will stay on-axis to monitor the beam. Fig. 3 shows the drawing of the three near detectors in the beamline. The left panel shows the scenario in which all three sub-detectors aligned on-axis, and the right panel shows the scenario in which ND-LAr and ND-GAr move off-axis while SAND is on-axis.

The most upstream detector in the DUNE ND complex is a modulated liquid argon TPC, named ND-LAr [8]. The ND-LAr detector serves as a primary target. It is designed to have a 50t fiducial mass, divided into 35 optically separated modules. Two readout systems are reading optical and charge signals in ND-LAr. The charge readout system employs a novel pixelated anode technique to precisely track the ionizing signals of the charged particles, and the light readout provides rejection of un-associated charge signals such as pile-up. The further downstream detector next to the ND-LAr is ND-GAr. The ND-GAr measures the momentum and sign of charged particles exiting ND LAr. In addition, as a target, the ND-GAr extends the ν-Ar interaction measurement capability by detecting charged particles in lower energies than achievable in the far or near Liquid argon detectors.

The most downstream detector, System of on-Axis Neutrino Detector (SAND), stays on-axis permanently. SAND monitors the beam stability and provides absolute flux measurement. In addition, SAND uses a different target material to validate the neutrino interaction modeling. The SAND system consists of a superconducting magnet, an electromagnetic calorimeter, an inner tracker, and a LAr target. The superconducting magnet and electromagnetic calorimeter are re-purposed from the KLOE experiment.

4. DUNE far detector

The DUNE far detector facility locates at Sanford Underground Research Facility in South Dakota. It is by far the deepest underground lab in the US with three main caverns in it. Two caverns host four detectors halls, and one cavern serves as a support cavern. The FD first module installation will start in the mid-2020s. The first three modules of DUNE FD will be liquid argon TPC, and the last will be the so-called Module Of Opportunity. A technical design report of the FD has been published in [9] [10] [11].

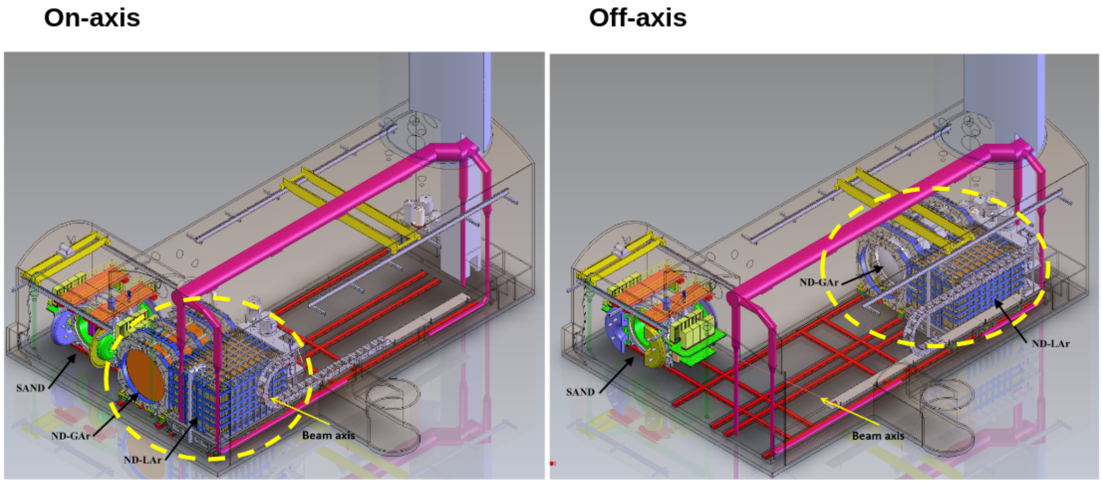

Figure 3: The DUNE near detector design.

The FD module 1 is designed to include a 3.6 m horizontal drift volume with vertical anode and cathode planes and a photon detector. The FD module 2 has a different design with a 6.5 m vertical drift volume with horizontal PCB (Printed Circuit Board) anode and cathode planes and a photon detector. The vertical drift design in module 2 has a longer drift distance than module 1. The DUNE prototype, ProtoDUNE, has demonstrated that electron lifetimes of tens of ms are achievable; thus, a longer drift distance is acceptable with much less cost. The key designs for module 2 include Drift along vertical direction and cathode plane in the middle; Readout on strips etched on PCBs; Two induction and one collection readout; Electronics for top drift volume accessible; Cathode near -300 kV for a drift field of 450 V/cm. Fig. 4 shows the FD module 1 and 2 sketches.

Many simulation studies have been completed to understand the performance of the FD horizontal drift module. There are three complementary algorithms. The first one takes the 2D (location vs. time) information from each readout plane and performs a pattern recognition algorithm on the 2D plane. Then a 3D image is reconstructed by combining all 2D reconstructions [12]. The second is to directly take 3D information, and the pattern recognition is completed with the 3D information [13]. The last is to use the Convolutional Visual Network (CVN) technique [14]. In general, to reconstruct the neutrino energy, tracks in FD are reconstructed based on the range for the contained case and multiple Coulomb scattering for the exiting case. The showers are reconstructed based on calorimetry. A 90% peak efficiency can be obtained for both ν_μ and ν_e. The left panel in Fig. 5 shows the ν_e signal and NC background detection efficiency in the FD overlaid with the expected neutrino spectrum. The right panel shows the CVN scores for different event categories. A very pure ν_e sample can be obtained with a cut at 0.85.

5. ProtoDUNE

Two kilo-ton scale prototype detectors for the FD modules have been operated at CERN since 2018. The two prototype detectors have two different designs, one with a single liquid phase design (ProtoDUNE-SP) [15] and the other with a liquid plus gaseous dual-phase design (ProtoDUNE-

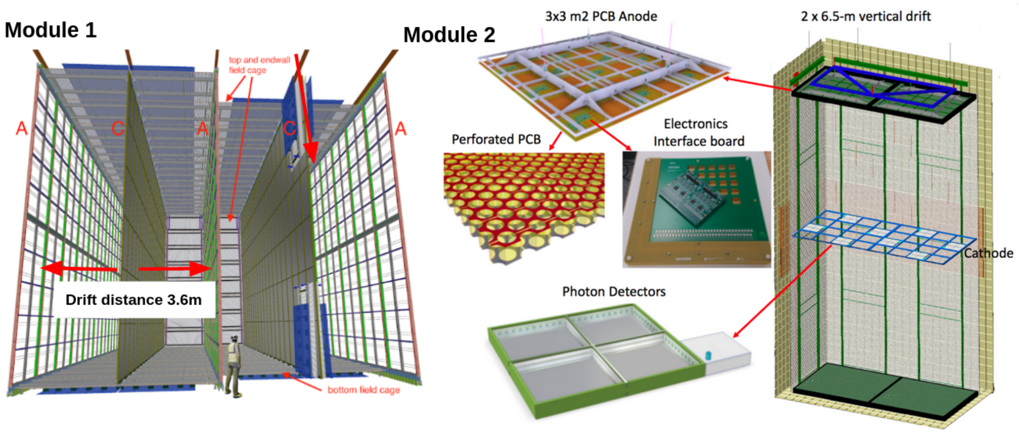

Figure 4: Sketch of the DUNE far detector module 1 (left) and module 2 (right).

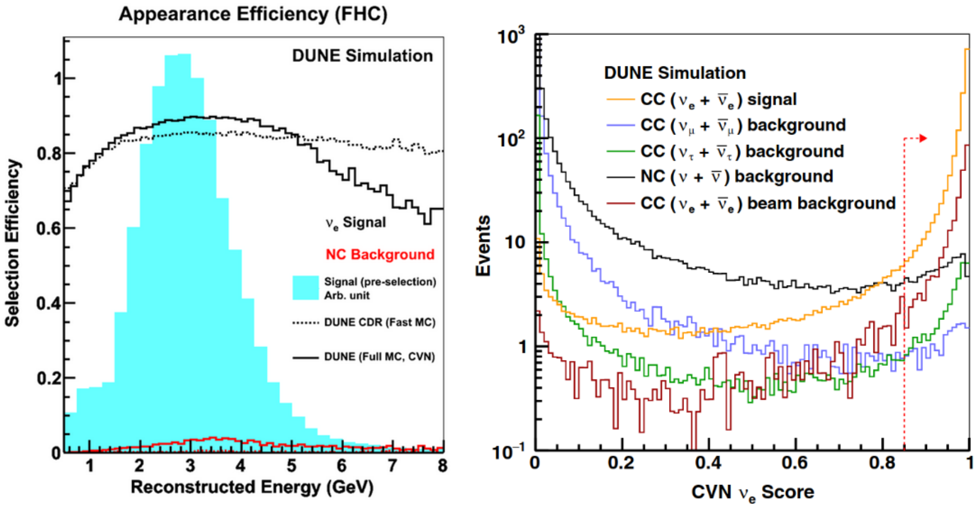

Figure 5: Reconstruction performance in FD. Left the selection efficiency vs. energy. Right the CVN signal selection performance. See text for detail. Figure is taken from [14].

DP) [16]. The single-phase detector has been accumulating data from 2018 to 2020, while the dual-phase detector has been accumulating data from 2019 to 2020. The single-phase phase II run will start in late 2022. The ProtoDUNE detectors are aimed at production and installation demonstration, detector performance validation with cosmics and beam charged particles, and photon detector demonstration. Several articles have been published to demonstrate the detection capability of the LArTPC detector [17], [18]. During the ProtoDUNE-SP run, the detector is very stable with 99% HV uptime,   99% live channels, and high purity (30 ms e-lifetime). The data in the protoDUNE detectors also validate the entire analysis chain in LArTPC. As an example, Fig. 6 shows the performance of the protoDUNE-SP with the charged particle beam test. The left panel shows the Signal-to-Noise ratio for the charge readout planes with cosmic data, and the right shows the dE/dx vs. range to demonstrate the particle identification power.

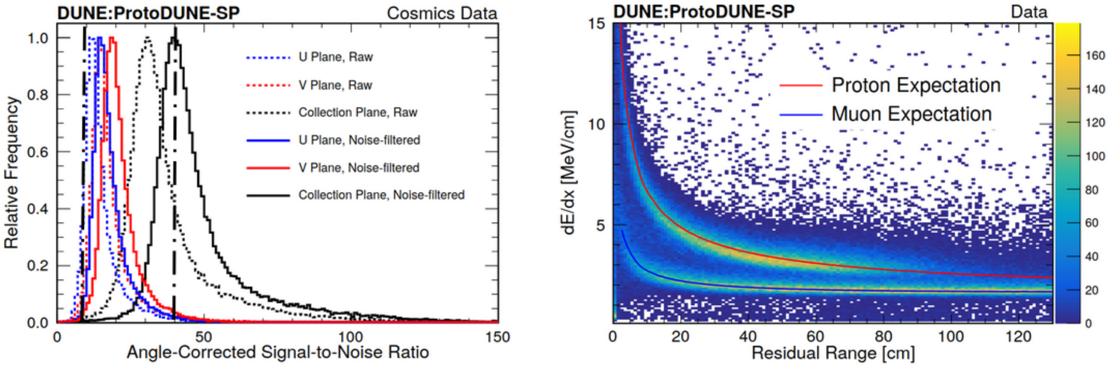

Figure 6: ProtoDUNE-SP performance. Left panel the signal-to-noise ratio at each readout plane. Right panel the dedx vs. range. See text for details. Figure is taken from [17].

6. Long-baseline physics sensitivity

In the long-baseline oscillation analysis, DUNE simultaneously fit two disappearance (ν_μ and $\bar{\nu}_\mu$) and two appearance (ν_e and $\bar{\nu}_e$) samples. A realistic treatment of the systematic uncertainties with constraints from ND is used. With seven years running time, an order of 10,000 and 1,000 events for disappearance and appearance channels can be obtained. An article detailing the fitting framework and the systematic uncertainty handling has been published in [19]. Fig. 7 and Fig. 8 show the DUNE sensitivity to the neutrino oscillation parameters. In Fig. 7, the square root of $\Delta\chi^2$ extracted by comparing a predicted zero δ_{CP} and a true δ_{CP} as a function of true δ_{CP} value with the assumption of normal hierarchy (left) and inverted hierarchy (right) is presented. Assuming a true δ_{CP} of $-\pi/2$, with 336 kt-MW-years running, five sigma sensitivity can be reached to exclude a zero δ_{CP}. In Fig. 8, the square root of $\Delta\chi^2$ extracted by comparing normal and inverted hierarchies as a function of true δ_{CP} value with the assumption of normal hierarchy (left) and inverted hierarchy (right) is presented. A five sigma determination of the mass hierarchy is expected with 336 kt-MW-years running.

7. Beyond the long-baseline neutrino oscillation measurement

DUNE can cover a broad range of measurements beyond the long-baseline neutrino oscillation measurement, particularly DUNE is sensitive to the supernova neutrino detection. A thorough analysis of the supernova burst signal in DUNE, including the time dependence of the energy and flavor profile and non-thermal spectral features, can open an opportunity to discover a broad range of supernova and neutrino physics phenomena, such as sensitivity to neutrino mass ordering, collective effects, and more topics. A detailed analysis can be found in [20].

In addition, DUNE provides a wide range of Beyond-Standard-Model measurements. DUNE can perform baryon number violation searches such as proton decay, given DUNE's unique sensitivity to decay. A combination of ND and FD can boost DUNE's sensitivity to the sterile neutrino measurements. Furthermore, both ND and FD can detect the dark matter candidates: ND can detect the beam-related, and FD can detect the external dark matter. There are plenty of additional measurements such as non-standard interaction, CPT violation, Non-unitarity of neutrino mixing

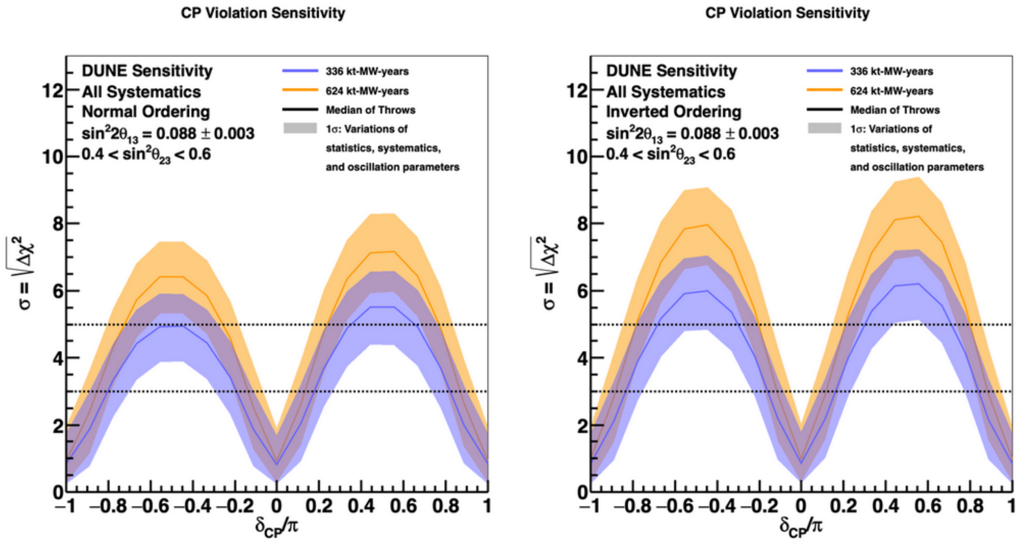

Figure 7: Sensitivity of the δ_{CP} measurement for normal (left) and inverted (right) hierarchy. See text for detail. Figure is taken from [19].

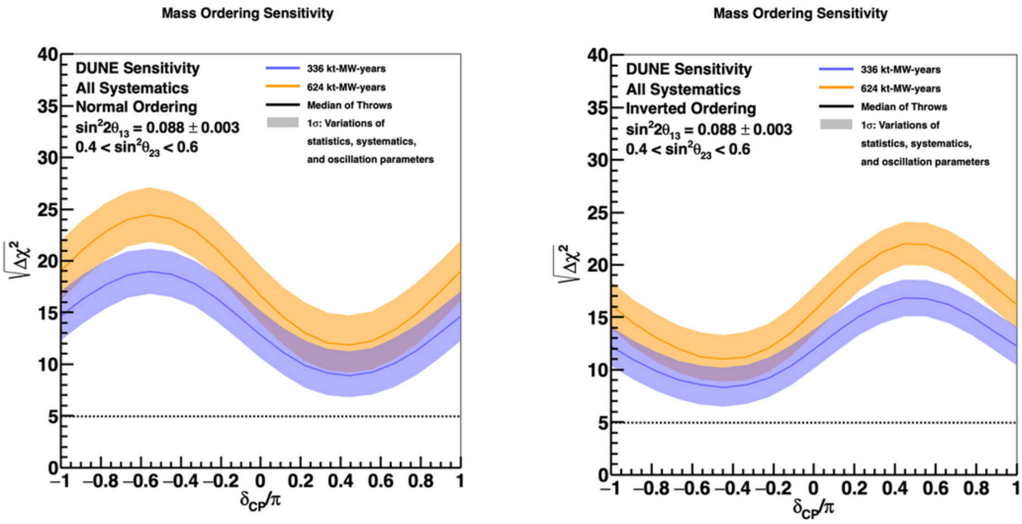

Figure 8: Sensitivity of the mass hierarchy for normal (left) and inverted (right) hierarchy. See text for detail. Figure is taken from [19].

matrix, neutrino trident at ND, which can be made. Detailed descriptions and results about the DUNE's capability beyond long-baseline oscillation can be found in [21].

8. Summary

DUNE provides a unique opportunity to measure the CP violation and mass hierarchy simultaneously thanks to:

- Broad-band high-intensity beam,

- Complex near detector able to disentangle degenerate systematic uncertainties,
- Massive deep-underground far detectors with a very long baseline,

and of course a significant number of diligent people. As an international collaboration, DUNE is working hard toward successful measurements with numerous detector design and prototyping efforts. Also, there is plenty of room for additional collaborators to enjoy the physics of DUNE.

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