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Review Article

The Deep Underground Neutrino Experiment

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The Deep Underground Neutrino Experiment (DUNE) is a worldwide effort to construct a next-generation long-baseline neutrino experiment based at the Fermi National Accelerator Laboratory. It is a merger of previous efforts and other interested parties to build, operate, and exploit a staged 40 kt liquid argon detector at the Sanford Underground Research Facility 1300 km from Fermilab, and a high precision near detector, exposed to a 1.2 MW, tunable ν beam produced by the PIP-II upgrade by 2024, evolving to a power of 2.3 MW by 2030. The neutrino oscillation physics goals and the status of the collaboration and project are summarized in this paper.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) has been established as an international partnership to fulfill the goals established by the Particle Physics Program Prioritization Panel in the United States [1]. The design, goals, and status of the collaboration, experiment, and project have been recently described in detail in a Conceptual Design Report (CDR) [2] written for a "CD-1 Refresh" review that took place in July 2015 for the U.S. Department of Energy.

Members of the international neutrino community broadly agree on the goals for study to remove gaps in our understanding of the neutrino sector in the current Standard Model of Particle Physics:

(i) determination of the mass ordering between the normal mass ordering ($m_3 > m_1$; NO) and the inverted ordering ($m_1 > m_3$; IO) (a common notation is to call these the normal hierarchy (NH) and inverted hierarchy (IH), but for the case of nonhierarchical degenerate neutrino mass, there is still sensitivity to the ordering, so this paper uses the slightly more precise notation NO and IO),

(ii) determination of the value of the CP (Charge Parity) violation phase δ,

(iii) determination of the octant of θ_{23},

(iv) more precision in the determination of the values of the mixing angles and Δm^2 values,

(v) search for new physics beyond the three-neutrino paradigm,

(vi) determination of the overall mass scale,

(vii) determination of whether the neutrino is Dirac or Majorana.

The first five issues can be addressed with precise new accelerator experiments with detectors located near and far from the proton target. One requires a deep underground location to reduce backgrounds in the search for neutrinoless double beta decay. Through the first two decades of the 21st century, a large variety of experiments have been proposed to accomplish this program. Since the scale in size and cost is larger than previous neutrino experiments, a large variety of solutions in terms of baseline, location, overburden, detector size, detector design, and beam energy spectrum have been investigated to achieve an optimum program. Many of the advocates of these programs have coalesced into a new international collaboration based on two facilities: the Fermilab accelerator complex that will host the Long-Baseline Neutrino Facility (LBNF) and the Sanford Underground Research Facility (SURF) located 1300 km away in South Dakota. LBNF will be operated as a fully international facility hosted by Fermilab. The detectors, totaling 40 kt fiducial mass of liquid argon, will be designed, built, commissioned, and operated by the international DUNE collaboration. The scope of LBNF includes an intense on-axis neutrino beam aimed at the far site, the conventional facilities at both the near and far sites, and the cryogenic infrastructure needed to support the DUNE detector at the far site. The DUNE detectors include a high-performance near neutrino detector, a beamline measurement system, and a massive liquid argon time projection chamber (LArTPC) for use as a neutrino detector deep underground at SURF.

DUNE and LBNF encompass an ambitious and long-term program to improve our knowledge of neutrino physics and particle astrophysics. They represent what will be a significant investment by the world's high energy physics community. The goals of the program will not be accomplished in a single phase. A partially applicable analogy is to look at the tremendous success of the LHC program as of 2015, even though it has not yet run at its design energy of 14 TeV. At the same time that the DUNE physics program is ambitious, the facility and detectors are also flexible in their ability to adapt to changing understanding of the neutrino sector or any new and unexpected physics beyond the three-neutrino paradigm that might be uncovered in the coming decade.

A previous look at potential future experiments and facilities, including the LBNE program in the United States and the Hyper-Kamiokande program in Japan, is provided in the last special issue on neutrino oscillations in [3]. A more detailed look at the science opportunities for LBNE was given in [4]. As this special issue focuses on neutrino mass and oscillations, in this paper I will cover only the oscillation physics of DUNE, and the status of the collaboration. In Section 2 I summarize DUNE's beam physics program. In Section 3 some complementary measurements using atmospheric neutrinos are discussed. Other physics capabilities, including nucleon decay, astrophysical neutrinos, and neutrino physics in the near detector are covered extensively in [2, 4]. I will not review the current design of the 1.2 MW beamline and the other facilities that are described in volume 3 of the CDR or describe in any detail the design for the 40 kt (fiducial volume) LArTPC that can be found in volume 4 [2]. In Section 4 I will summarize the current status and timeline for DUNE and LBNF.

2. Neutrino Oscillation Physics Capabilities Using the NuMI Beam

SURF is located 1300 km from Fermilab. A study of baseline optimization for the measurement of CP violation, mass ordering, and θ_{23} octant in a long-baseline experiment concluded that a detector at a baseline of at least 1000 km in a wide-band ν_μ beam is the optimal configuration [5]. SURF well satisfies this requirement and as the site of the original Davis solar neutrino experiment was thoroughly investigated as a candidate site for a Deep Underground Science and Engineering Lab, it is well suited for a large scientific endeavor. Briefly the optimization comes from the fact that CP violation and matter effects, which are sensitive to the mass ordering, both cause a difference in the rate of neutrino and antineutrino oscillation events. But those differences are different. The size of the asymmetry from the matter effect grows with increasing baseline and dominates for a baseline over 1000 km.

Table 1: Integrated rates of CC-like events. Signal ν_e rates are shown for both NO and IO and $\delta_{\mathrm{CP}} = 0$. Background rates assume NO.

(150 kt·MW·yr)	ν mode	$\overline{\nu}$ mode
ν_e signal NO (IO)	861 (495)	61 (37)
$\overline{\nu}_e$ signal NO (IO)	13 (26)	167 (378)
Total signal NO (IO)	874 (521)	228 (415)
Beam $\nu_e + \overline{\nu}_e$ CC Bkgd	159	89
NC Bkgd	22	12
Beam $\nu_\tau + \overline{\nu}_\tau$ Bkgd	42	23
Beam $\nu_\mu + \overline{\nu}_\mu$ Bkgd	3	2
Total Bkgd	226	126
ν_μ ($\overline{\nu}_\mu$) signal	10842	3754
$\overline{\nu}_\mu$ (ν_μ) Bkgd	958	2598
NC Bkgd	88	50
Beam $\nu_\tau + \overline{\nu}_\tau$ Bkgd	63	39

The oscillation probabilities for ν_e ($\overline{\nu}_e$) appearance in a ν_μ ($\overline{\nu}_\mu$) beam at the Fermilab/SURF distance are shown in Figure 1 as a function of neutrino energy for several possible values of the CP phase parameter δ_{CP}. These curves illustrate the choice of a broadband beam that can not only measure the rate of ν_e and $\overline{\nu}_e$ appearance but also map out the spectrum down to energies of 500 MeV.

Figure 1 also shows the decision about beam optimization, such as the choice of proton momentum. That choice involves tradeoffs in secondary particle production, cycle time, and beam power, all of which affect the integrated flux. The reference design in Chapter 3 of the CDR [2] has chosen a proton beam energy of 80 GeV, a beam power (after the PIP-II upgrades) of 1.07 MW, a graphite target, a horn current of 230 kA, and a 4 m diameter decay pipe that is 204 m long. Further optimizations of these parameters are continuing and some improvements in sensitivity can be expected as reflected in the curves labeled "optimized design" in some of the sensitivity plots in this paper. A discussion of efforts to optimize the LBNF beam design can be found in Section 3.7 of volume 2 of the CDR [2].

Signal and background event rates assuming a 150 kt·MW·yr exposure in each of a neutrino and antineutrino beam are shown in Table 1. This and all subsequent figures assume an exposure of 300 kt·MW·yr which corresponds to 3.5 years each in neutrino and antineutrino mode, a 40 kt fiducial volume detector and a 1.07 MW 80 GeV beam. This includes the assumption of equal duration runs of neutrinos and antineutrinos, but that split can be adjusted depending on the early results of this and other neutrino experiments, such as NOνA and T2K [6, 7], to maximize parameter sensitivity. The spectra of reconstructed ν_μ and ν_e signal and background events are shown in Figures 2 and 3. These spectra are used in the accurate determination of neutrino oscillation parameters.

The 1300 km baseline allows the neutrino and antineutrinos in the NuMI beam to travel through enough matter to be affected by the MSW effect. This leads to a large asymmetry

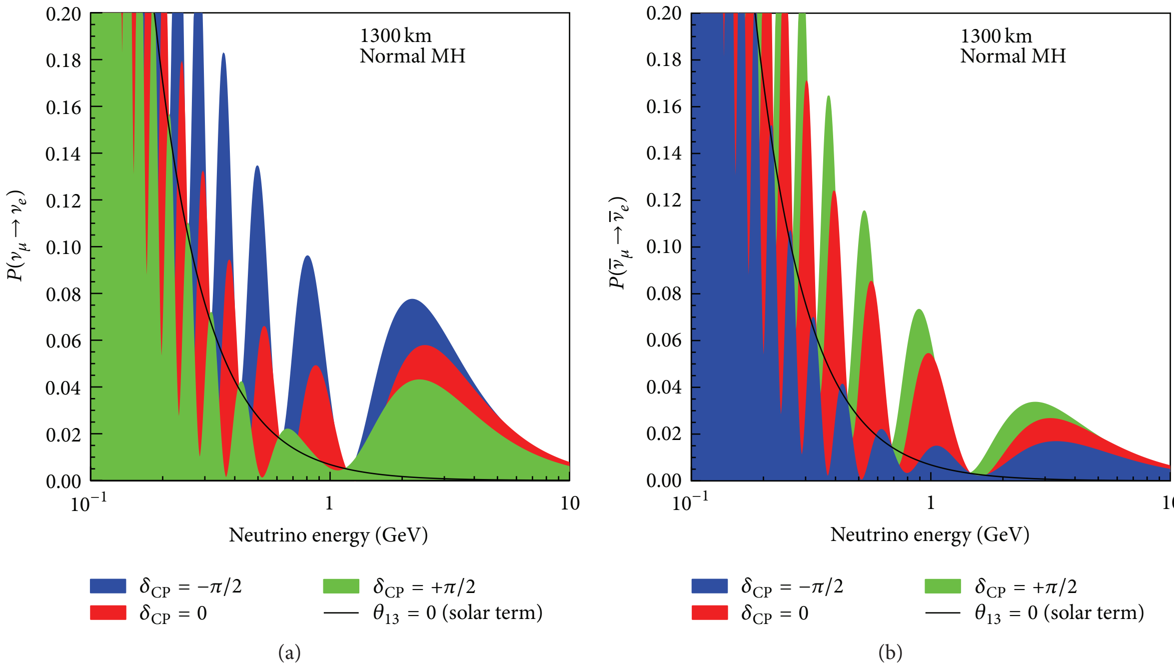


FIGURE 1: The appearance probability for ν_e (a) and $\overline{\nu}_e$ (b) as a function of neutrino energy in a $\nu_\mu/\overline{\nu}_\mu$ beam. The curves are calculated for 1300 km baseline and NO, three values of δ_{CP} for the Daya Bay best fit value of θ_{13} and for $\theta_{13} = 0$.

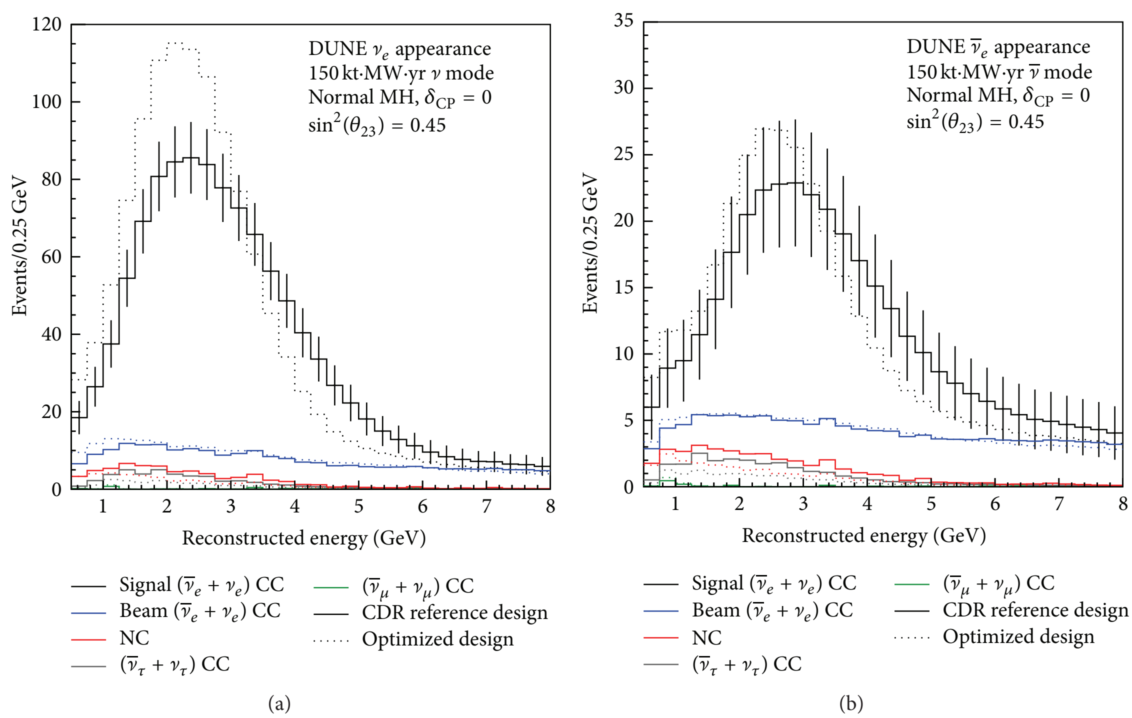
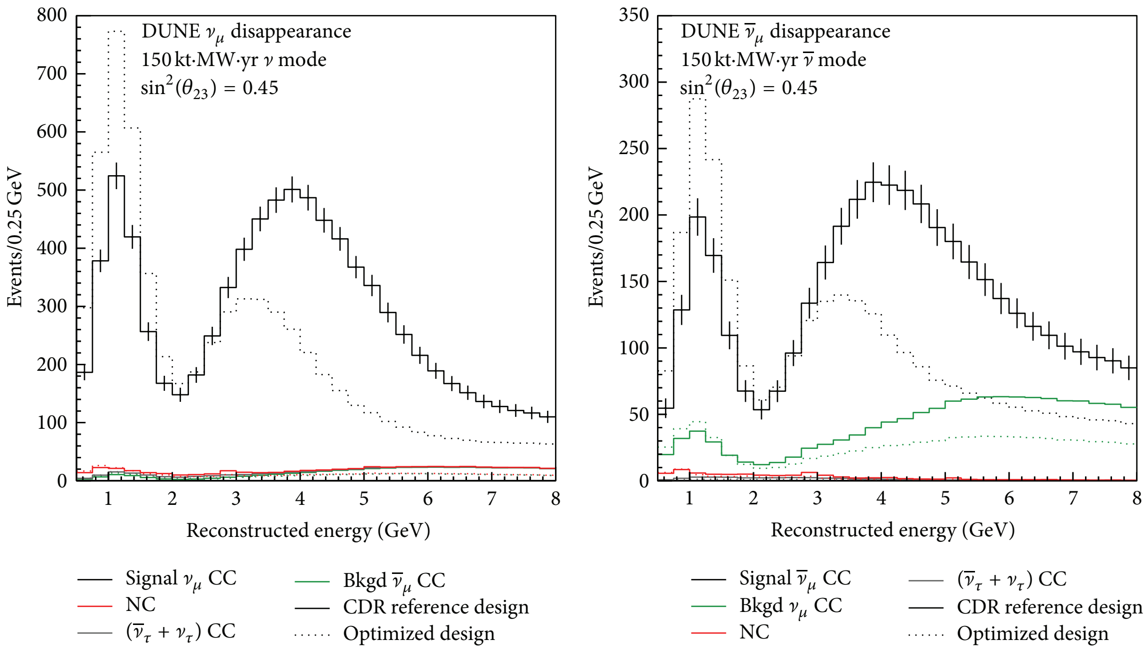
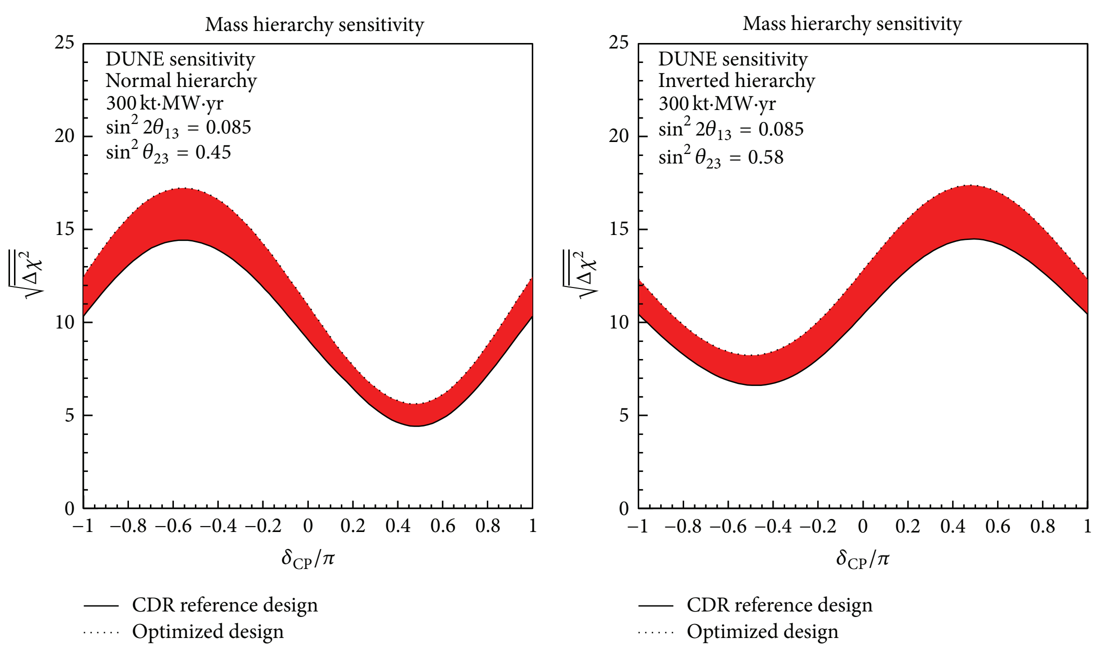


FIGURE 2: Reconstructed energy distributions of selected $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance events for 150 kt·MW·yr exposure, assuming NO and $\delta_{CP} = 0$. Event rates and backgrounds are shown both for the reference design (solid) and for an optimized beam (dots) which has been designed but not fully costed.



(a) (b)

FIGURE 3: Reconstructed energy distributions of selected ν_μ and $\overline{\nu}_\mu$ events for 150 kt·MW·yr exposure, assuming NO and $\delta_{CP} = 0$.

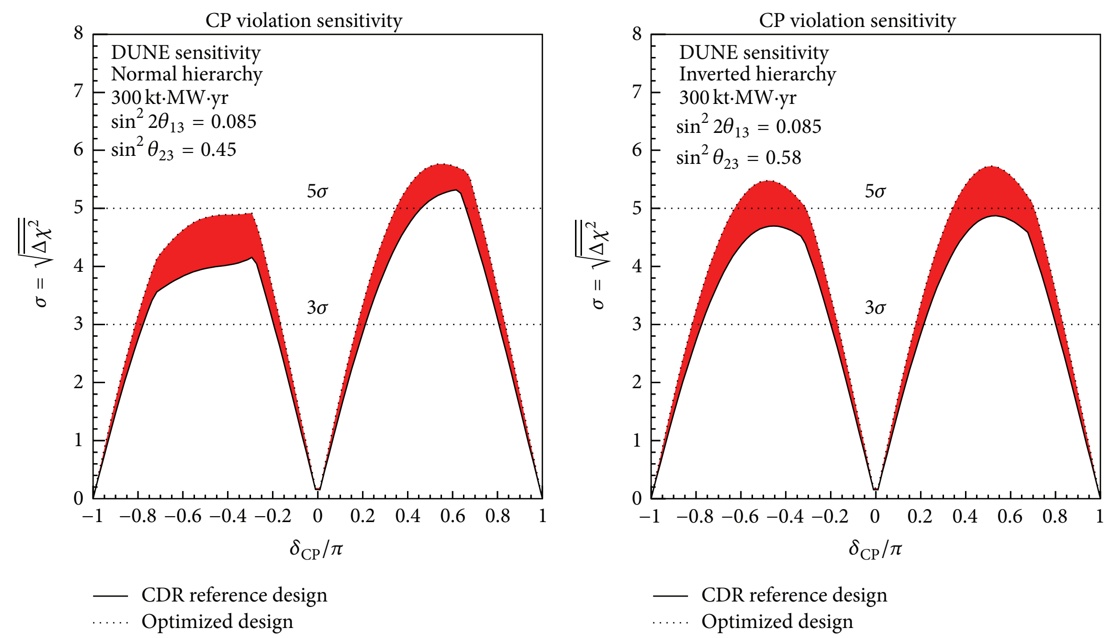


(a) (b)

FIGURE 4: These figures show the sensitivity with which the mass ordering can be determined using the LBNF beam as a function of δ_{CP} for the NO (a) and IO (b). The shaded region shows the range between the CDR reference design and a possible optimized design of the beam.

in the $\nu_\mu \rightarrow \nu_e$ versus $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation probabilities, the sign of which depends on the mass ordering. There are only two possible values of the ordering, and the asymmetry in the region of the peak flux for DUNE is ±40%, larger than the maximal possible asymmetry due to CP violation.

Figure 4 shows how well the mass ordering (called the mass hierarchy in the figures) can be measured as a function of δ_{CP} using beam neutrinos. The areas of lower sensitivity are for values of the ordering and δ_{CP} where the total asymmetry is smaller, and the better sensitivity happens where the total



(a) (b)

Figure 5: These figures show the sensitivity with which CP violation can be established using the LBNF beam as a function of δ_{CP} for the NO (a) and IO (b). The shaded region shows the range between the CDR reference design and a possible optimized design of the beam.

asymmetry is larger. The value of θ_{23} is important, affecting both the statistics and the sensitivity (in opposite directions) to the ordering and to CP violation. Nevertheless, DUNE will be able to unequivocally measure the mass ordering in the three-neutrino paradigm for any values of neutrino oscillation parameters. Note that a conversion of $\Delta\chi^2$ to significance takes some care, as discussed in [8].

The magnitude of CP violation in the neutrino sector depends on a combination of neutrino oscillation parameters known as the Jarlskog invariant:

$$J_{CP}^{PMNS} \equiv \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}. \quad (1)$$

Since the value of θ_{13} is now known, the minimal conditions required for measuring δ_{CP} in the three-neutrino paradigm have been met; all three mixing angles and both mass splittings have been measured and are nonzero. This will introduce an asymmetry between neutrino and antineutrino oscillations unless $\delta_{CP} = 0$ or π. Even then, the value of the parameter δ_{CP} can be well measured, but CP violation in the neutrino sector can only be measured if those two possible values are ruled out. Either a precise measurement of or a stringent limit on CP violation would be quite interesting and challenging for theorists who believe that CP violation in the lepton sector may be related to the baryon-antibaryon asymmetry in the universe.

Figure 5 shows the significance with which the CP violation can be measured as a function of δ_{CP} for an exposure of 300 kt·MW·yr assuming the NO and the IO. The shaded region represents a range in possible sensitivity from the reference design (pessimistic) to an optimized design (optimistic). Using the reference design, DUNE will achieve a greater than 3σ measurement of CP violation for 75% of δ_{CP} values in 1320 kt·MW·yr, and a 5σ measurement of CP violation for 50% of δ_{CP} values in 810 kt·MW·yr. An exposure of 1320 kt·MW·yr is the suggested goal from the P5 report [1], an ambitious but achievable exposure for this facility in the long term.

A value of θ_{23} of exactly 45° would indicate that ν_μ and ν_τ have equal contributions from ν_3, which would be evidence for a new symmetry. A value greater than 45° would indicate mixing among the generations of the neutrino sector qualitatively different than in the quark sector (in addition to the different mixing angles). Thus, it is important to measure θ_{23} with enough precision to determine the octant or the nondeviation from 45°. The measurement of $\nu_\mu \rightarrow \nu_e$ is sensitive to $\sin^2(\theta_{23})$ while ν_μ disappearance is sensitive to $\sin^2(2\theta_{23})$. DUNE will measure both of these and will probe the θ_{23} octant precisely. The sensitivity as a function of the true value of θ_{23} is shown in Figure 6. A strong indication of the octant can be found over most of its currently allowed range.

Systematic uncertainties in the accelerator neutrino measurements with DUNE will come from uncertainties in the neutrino flux after near/far extrapolation, the interaction model, the ν_μ and ν_e reconstructed energy scales, and the fiducial volume. DUNE plans to take advantage of spectral analysis, meaning that absolute and relative flux normalization is required. Based on previous experience from the NuMI beam, a goal uncertainty of 2% has been set on ν_e signal normalization relative to the ν_μ rate, added in quadrature

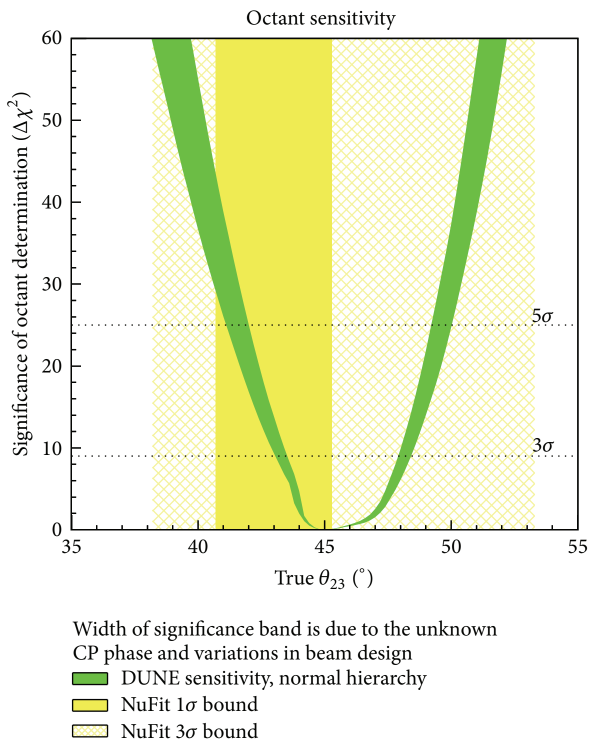


FIGURE 6: This figure shows the sensitivity with which the quadrant of θ_{23} can be determined using the LBNF beam as a function of its true value. The green shaded region shows the range due to variations in beam design and the true value of δ_{CP}. The yellow region shows the current best fit value for NO from a global fit from the NuFit collaboration.

with an overall 5% normalization. Uncertainty in neutrino interaction models comes from the relative rates of quasi-elastic, resonance, and deep inelastic scattering in nuclei, together with final state interactions. Significant improvements to neutrino interaction models are anticipated as a result of the intermediate neutrino program [9] and the goal for the effect of uncertainties is 2% after cancellation from the near/far comparison. Previous experiments have achieved uncertainties in the energy scale below 3%, and DUNE will take advantage of a number of liquid argon detectors being studied in test beams, in neutrino beams for the short-baseline program [10] and in the intermediate neutrino program [9]. The effect of fiducial volume uncertainty is reduced in large detectors such as DUNE and will be about 1%. The total systematic error on the ν_e appearance rate is estimated at 3.6% and should be reduced by the time the statistical error gets down to that level.

The high-precision near detector of DUNE will be able to make a number of cross section measurements that will help in the extrapolation of the neutrino flux to the far detector. Should any anomalies remain after the SBN program and its search for sterile neutrinos [10], the near and far detectors together will be able to provide further understanding of the effects or constrain the physics involved. There are a variety of other new physics possibilities, such as nonstandard interactions, neutrino decay, and Lorentz violation that DUNE will be able to investigate or constrain. While these are not the primary goals of DUNE and they entail no additional requirements on the detector, the remarkable capabilities of DUNE allow for the study of many possible extensions of the three-neutrino paradigm, should any exist.

3. Neutrino Oscillation Physics Capabilities Using Atmospheric Neutrinos

Atmospheric neutrinos come in all flavors and in a wide range of baseline, neutrino energy, and hence L/E_ν. They are particularly sensitive to θ_{23} and were the source of the atmospheric neutrino anomaly leading to the discovery of neutrino mass and oscillations by Super-Kamiokande in 1998 [11].

The transitions between electron neutrinos and muon neutrinos are affected by MSW transitions for the longest traveling atmospheric neutrinos $\cos\theta_z \sim -1$, where θ_z is the zenith angle. There is an enhancement for neutrinos in the normal mass ordering and antineutrinos in the inverted mass ordering. From [4] the rates of fully contained ν_e, fully contained ν_μ, and partially contained ν_μ are shown as a function of zenith angle for no oscillations, normal ordering, and inverted ordering (Figure 7). Differences in the event rates as a function of θ_z are observed in comparing the NO and IO predictions at low values of $\cos\theta_z$.

Since the enhancement occurs for neutrinos (antineutrinos) in the NO (IO), the sensitivity is enhanced if neutrino and antineutrino events are separated. There are no current plans to magnetize DUNE; however, its high-resolution imaging capabilities provide the ability to measure recoil protons and decay electrons that can be used to statistically tag neutrinos and antineutrinos. Recoil protons occur more often in neutrino interactions and can be tagged with 100% efficiency if the kinetic energy is greater than 50 MeV. Decay electrons in ^{40}Ar occur for μ^+ made by antineutrinos, but only 25% of the time for neutrino-induced μ^-.

For atmospheric neutrinos, the ordering sensitivity is essentially independent of δ_{CP}, in contrast to the beam neutrinos. This provides complementarity. In the three-neutrino paradigm, a joint fit of the atmospheric and beam neutrinos for the mass ordering increases the significance of the ordering measurement for those values of δ_{CP} in Figure 4 where the significance is lowest. For all regions of δ_{CP} atmospheric neutrinos provide a consistency check of the ordering determination which can be used as a test for new physics.

4. Status of the DUNE Collaboration

The international context and motivation for a long-baseline neutrino experiment is well described in [3] from the last special issue on neutrino physics and oscillations. In that document, ideas for approaches to future long-baseline neutrino facilities in the US, Europe, and Japan are described. Since that time, the P5 report in the United States [1] and the strategy document for particle physics in Europe [12] have helped to shape the direction of the field. In particular, a

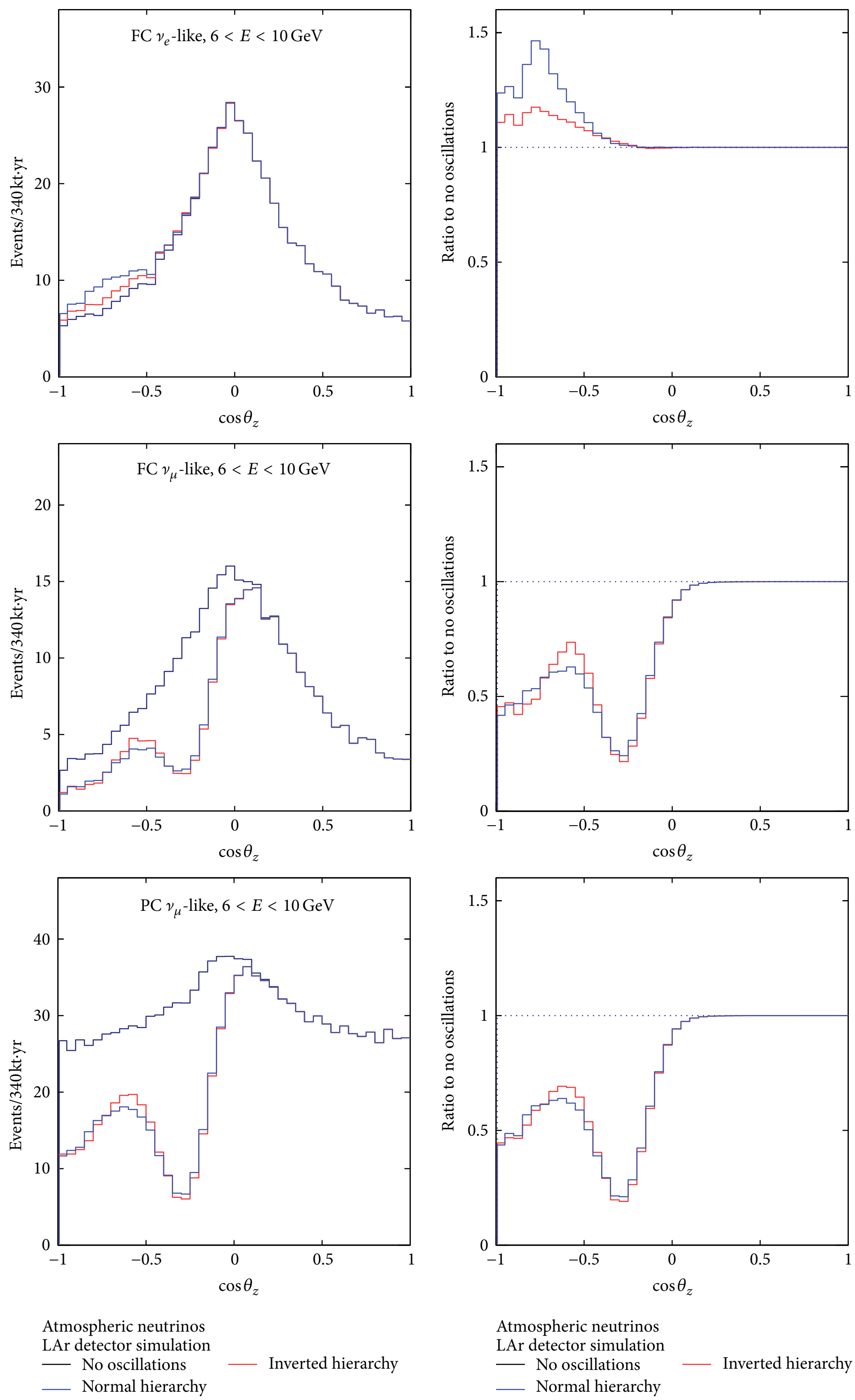


FIGURE 7: Reconstructed angles of atmospheric neutrinos in DUNE for 6 to 10 GeV fully contained ν_e and ν_μ and partially contained ν_μ events. Distributions and ratios to the no oscillation case are shown for normal and inverted mass orderings.

conclusion of the European report was that CERN should help the European neutrino community participate in a long-baseline neutrino project outside of Europe. DUNE is made up of many former members from the LBNE and LBNO collaborations as well as many additional interested parties. It seems likely to grow to well over 1000 scientists during its phases of construction, installation, and operation. The collaboration formally adopted its rules in April of 2015. (Between the time of the P5 report and the formal start of the DUNE collaboration, it used the name ELBNF, for Experiment at the Long-Baseline Neutrino Facility.) It presently consists of 773 scientists from 144 institutions in 26 countries.

The P5 report specifically recommended that the previous efforts for a Fermilab-to-SURF long-baseline experiment be reformulated as an international collaboration [1]. The US involvement in the LHC at CERN has been seen as a successful example of international collaboration. A management structure paralleling those used at the LHC experiments has thus been established, a host lab providing the facilities, together with an international collaboration to build and operate the detector(s). The management structure of the collaboration includes two spokespersons elected by the collaboration, a technical coordinator, and a resource coordinator jointly appointed by the spokespersons and the Fermilab Management. An International Advisory Committee (IAC) consists of representatives from regional partners (such as CERN) and funding agencies that make major contributions to LBNF/DUNE. It advises the Department of Energy (DOE) and Fermilab and provides high-level global coordination. The Resources Review Board (RRB) has representatives from all the funding agencies. It provides focused monitoring and oversight of the projects. The Long-Baseline Neutrino Committee (LBNC) provides scientific peer review as an adjunct to the Fermilab Physics Advisory Committee (PAC). The Experiment-Facility Interface Group (EFIG) helps to ensure coordination between the detector systems from DUNE and technical infrastructure from LBNF for both the near and far detectors.

A letter of intent for DUNE was prepared and submitted to Fermilab in January of 2015 [13]. As mentioned above, the collaboration was formally established in April of 2015, it elected leaders, and core project leaders were appointed in parallel. A Conceptual Design Report was prepared and reviewed in July of 2015 by the Department of Energy in a process called CD-1 refresh (details of presentations can be found at https://web.fnal.gov/project/LBNF/ReviewsAndAssessments/SitePages/Home.aspx under "DOE reviews"). A high-level schedule for both the facility (LBNF) and detector (DUNE) construction and operation is shown in the CDR. At the request of the collaboration, early priority has been given to work at the far site. Site preparation will be complete in time coincidence with the completion at SURF of the rehabilitation of the Ross Shaft in late 2017. Four 10 kt fiducial mass liquid argon modules are scheduled to become operational between 2024 and 2027.

As DUNE is being developed, a multipronged short-baseline neutrino program will be carried out at Fermilab [10]. That is part of the response to the P5 call for a coherent short- and long-baseline program of neutrino experiments. The three detectors, SBND, MicroBooNE, and ICARUS, all use liquid argon time projection chambers and provide an opportunity to test both the hardware and software that is envisaged for DUNE. The intermediate neutrino program [9] includes other neutrino measurements that will help in the precise understanding of neutrino cross sections and the measurements of other possible backgrounds [9]. And the CERN Neutrino Platform will include tests of present and possible future designs for the liquid argon readout in realistic conditions.

5. Summary

It could be claimed that, so far, nature has been kind to the neutrino physics community since, despite the smallness of the neutrino cross sections, it has been possible to measure the mixing angles and Δm^2 values robustly in multiple ways [14]. Perhaps this favor will persist and CP-violating effects in neutrinos will be large and DUNE will have a long program of precisely measuring δ_{CP} and searching for new physics beyond the three-neutrino paradigm. But whatever nature has in store for us, the 25+ year DUNE/LBNF physics program has been designed to provide a detailed, careful, and fruitful look at the properties of neutrinos, long considered the least understood element of the Standard Model, and exploit the large, high-resolution underground far detector for nonaccelerator physics topics such as atmospheric neutrinos, the search for nucleon decay, and the measurement of astrophysical neutrinos, especially those from a core-collapse supernova.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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