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DUNE Physics*

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Abstract

The Deep Underground Neutrino Experiment is a worldwide effort to build a next-generation long-baseline neutrino experiment with a neutrino beam and near detector at Fermilab and a far detector at the Sanford Underground Research Facility 1,300 km from Fermilab. It is a merger of previous efforts and other interested parties to build, operate and exploit a staged 40-kt liquid argon detector and a high precision near detector exposed to a high-power, broad-band neutrino beam. The goals of the experiment are precision oscillation measurements, including CP violation and neutrino mass hierarchy determination, search for nucleon decay, and neutrino astrophysics, as well as precision neutrino physics at the near site.

INTRODUCTION

The DUNE Collaboration[1] plans to address a number of the fundamental open questions in particle physics and astroparticle physics utilizing a massive liquid argon time-projection chamber (LAr TPC) located at a depth of 4,300 meters water equivalent at the Sanford Underground Research Facility (SURF) in Lead, South Dakota; a high-power, broad band, sign-selected ν_μ beam at Fermilab with a baseline distance from source to detector of 1,300 km; and a precision neutrino detector located on the Fermilab site[2]. The primary science objectives[3] include: neutrino oscillation physics to search for CP is violation in the leptonic sector, determine the ordering of the neutrino mass eigenstates, make precision measurements of oscillation parameters, test the three-neutrino paradigm; searches for baryon number violating processes (nucleon decay); and neutrino astrophysics, most notably precision measurements of neutrinos from a core-collapse supernova within the Galaxy, should one occur during the multi-decade lifetime of the experiment.

DUNE is a newly formed international collaboration, with strong representation from the previous LBNE, LBNO and other collaborations. As of the time of *NuFact15*, DUNE had 776 collaborators from 144 institutions located in 26 different countries on five continents. The DUNE Collaboration will design, build, commission and operate the near and far detectors[4] and is responsible for carrying out the scientific program utilizing them.

Facilities necessary to mount this experiment[5], including the neutrino beam[6], the cryostats and cryogenics systems to house the LAr TPC far detector, and conventional facilities at both Fermilab and SURF will be designed, built and commissioned by the Long-

Baseline Neutrino Facility (LBNF) Project. A new, broad-band and tunable neutrino beam is being designed, optimized for the Fermilab-SURF baseline. It will be driven by a 1.2 MW proton beam provided by the PIP-II upgrade[7], and is designed to accommodate future beam power upgrades to 2.4 MW. The design of the beam is still being optimized, and physics results are presented below for different options currently under study. LBNF is a U.S. Project based at Fermilab with contributions from a number of international partners.

THE DUNE DETECTORS

The far detector[4] is a 40 kt fiducial mass (∼70 kt total mass) LAr TPC, located deep underground at SURF. The detector is divided into four independent 10 kt modules, each housed in its own cavern, as shown in Fig. 1. The detectors are placed in cryostats each of inner dimension 15 m wide × 14 m high × 62 m long. This arrangement allows for a staged construction and gives flexibility for evolution of the LAr TPC technology. While the cryostats will be identical, the LAr TPC detectors may not be, allowing lessons learned from the construction of the first module or information gleaned from the DUNE or other R&D programs to be incorporated in subsequent modules.

The reference design is a single-phase LAr TPC, which is an evolution of the successful ICARUS design[8] and in which alternating anode and cathode planes divide the liquid volume into four 3.6 m drift regions. The reference design is supported by development programs at Fermilab (the DUNE 35 t prototype, MicroBooNE[9], the Fermilab Short-Baseline Neutrino Program[10], and LArIAT[11]) and at CERN (ICARUS/WA104[12] and the DUNE Single-Phase Prototype[13]). Dual-phase readout technology, which is being developed by the WA105 Collaboration[14], is a potential alternate design that if demonstrated could form the basis for the second or subsequent 10 kt modules.

The DUNE near detector must constrain the systematic uncertainties for the oscillation analysis, which requires it to have the capability to precisely measure exclusive neutrino interactions of all four species in the beam: $\nu_\mu, \bar{\nu}_\mu, \nu_e$, and $\bar{\nu}_e$. This naturally results also in a self-contained non-oscillation neutrino physics program that exploits the intense LBNF beam. The reference design is a NOMAD-inspired[15] Fine-Grained Tracker (FGT)[4] illustrated in Fig. 2. It consists of a central straw-tube tracker with embedded nuclear targets, including high-pressure argon-filled tubes and calcium (A=40) targets, and a lead-scintillator

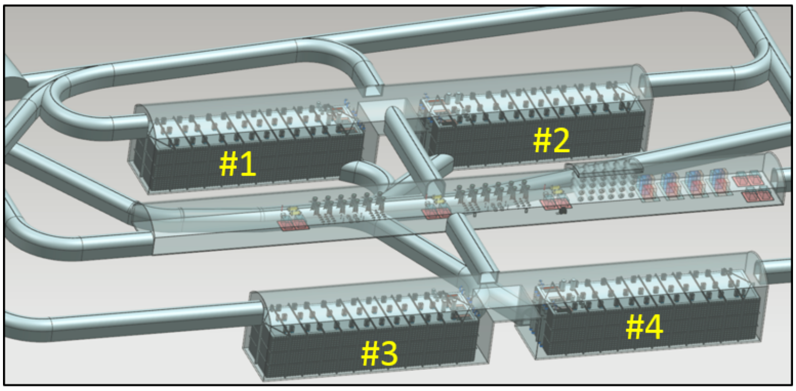

FIG. 1: Layout of the four caverns that will house the four 10-kt fiducial mass LAr TPC DUNE detectors at the Sanford Underground Research Facility

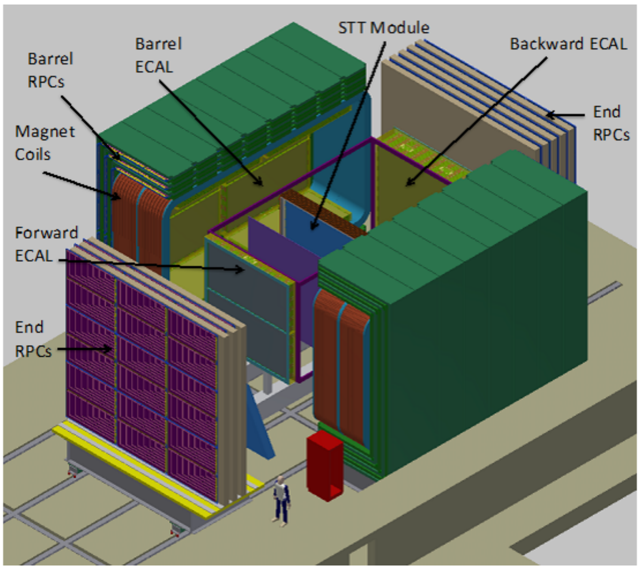

FIG. 2: The DUNE near detector reference design.

sampling electromagnetic calorimeter, both inside a large-aperture dipole magnet. An RPC-based muon identification system is embedded in the magnet yoke and in steel walls up- and down-stream of the magnet. DUNE has established a task force to perform an end-to-end physics study of the FGT capabilities to support the long-baseline analysis and to quantify the potential benefits of augmenting it with a LAr TPC or high-pressure gaseous argon TPC. Further details about the DUNE near detector can be found in [16].

THE DUNE SCIENCE PROGRAM

The primary scientific program of LBNF/DUNE addresses key science questions highlighted in the P5 report[17]. This program focuses on three areas: 1) Neutrino oscillation physics to probe CP violation (CPV) in the leptonic sector, determine the neutrino mass hierarchy (MH), and make precision measurements of oscillation parameters to test the three-neutrino paradigm; 2) Search for nucleon decay, particularly in modes such as $p \to K^+\bar{\nu}$ which are difficult for existing experiments to access; and 3) Supernova burst physics, exploiting the sensitivity of an LAr TPC to ν_e (as opposed to $\bar{\nu}_e$). Any of these would represent a major discovery. It is these science objectives that drive the design of LBNF and DUNE.

In addition, there is a high-priority ancillary science program that is enabled by the intense LBNF beam, the very long baseline, and the precision DUNE detectors. This program includes: 1) Other oscillation physics with beyond-the-Standard-Model sensitivity such as non-standard neutrino interactions, sterile neutrinos, or measurements of ν_τ appearance; 2) Oscillation physics with atmospheric neutrinos; 3) Neutrino physics with the near detector such as neutrino cross-sections, electroweak physics, nuclear and QCD physics; and 4) Searches for signatures of dark matter.

DUNE will exploit the high-intensity, broad-band LBNF neutrino beam and the 1,300 km baseline to make a comprehensive set of neutrino oscillation measurements to determine the MH, probe CPV, determine the θ_{23} octant, test the 3-flavor paradigm, and search for ν non-standard interactions in a single experiment. The long-baseline and wide-band beam allow measurement of oscillation effects over a broad range of energies, covering more than one full oscillation cycle as illustrated in Fig. 3. With a 1,300 km baseline, matter effects are at the 40% level, which allows for an efficient determination of the mass ordering and clean separation of CP violating effects from the matter effect.

Sensitivities for determining oscillation parameter are evaluated using a fast Monte Carlo[18], GLoBES[19] and GENIE[20]. The fast MC simulates detector response by smearing energies and angles at the final-state particle level based on measurements by ICARUS[8] and ArgoNeuT[21]. It "reconstructs" the neutrino energy, uses a kNN-based multivariate technique for ν_e "reconstruction," and generates parameterized efficiencies for input to GLoBES. Examples of the fast MC results are shown in Fig. 4.

Sensitivities for CPV and MH determination are shown in Fig. 5 as a function of the

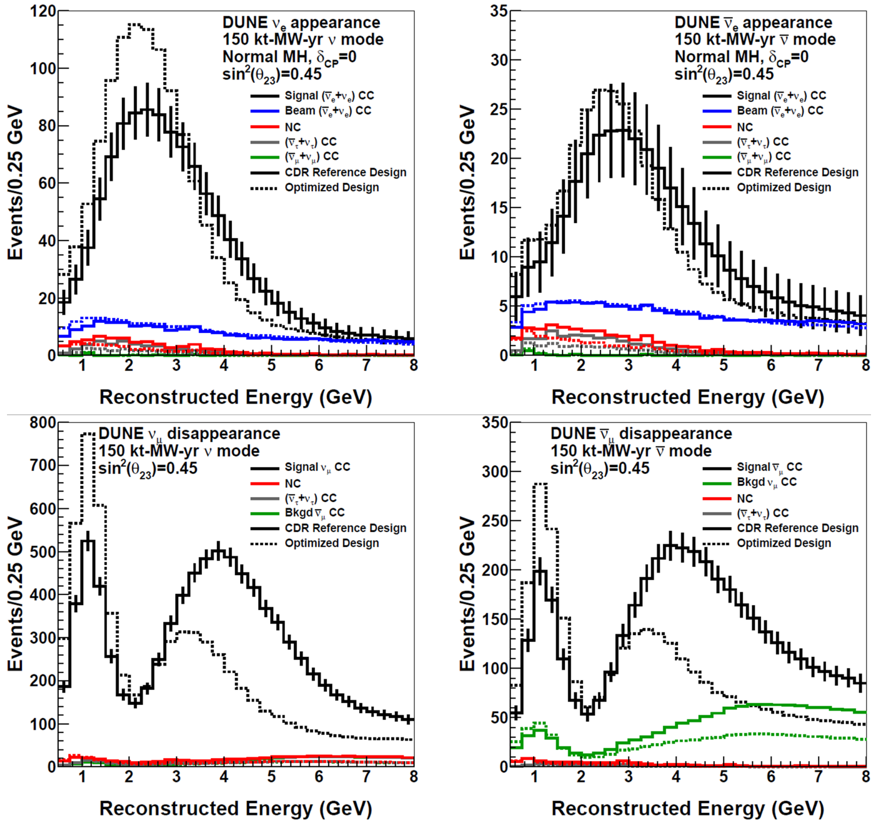

FIG. 3: ν_e appearance (top) and ν_μ disappearance (bottom) spectra in the LBNF ν (left) and $\bar{\nu}$ (right) beams. Spectra are shown for two different target-horn systems[6].

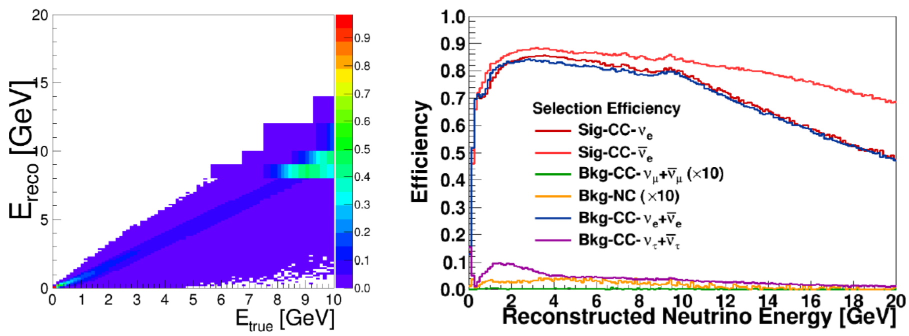

FIG. 4: Reconstructed versus true neutrino energy for charged-current ν_e events (left) and selection efficiencies for ν_e appearance events and principle backgrounds (right).

product of detector mass × beam power × time. Sensitivities are estimated the normal MH, but the MH and θ_{23} octant assumed to be unknown. CPV discovery sensitivity is expressed as the minimum significance over 50% of δ_{CP} values for determining that $\delta_{CP} \neq 0$ or π. Results are shown for two different beam designs and for a range of systematic errors[22]

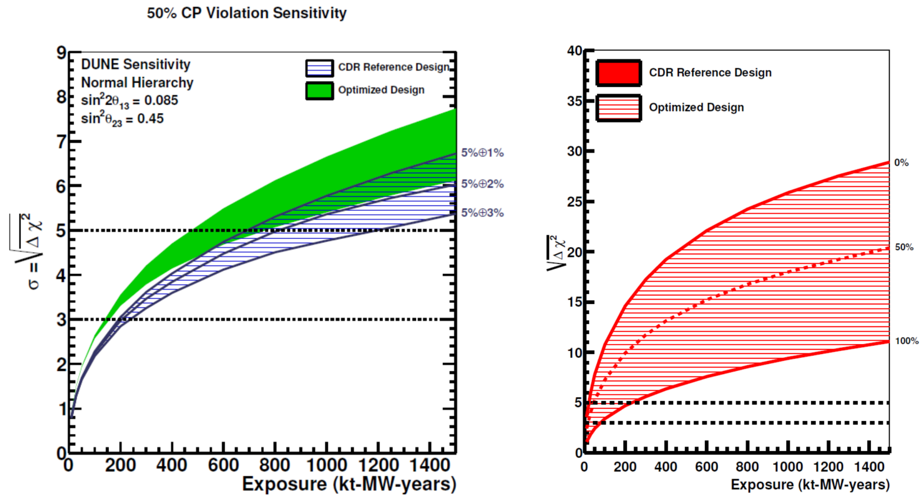

FIG. 5: Minimum significance for CPV discovery for 50% of the range of δ_{CP} as a function of exposure for two different beam designs and a range of systematic errors (left). Minimum significance for MH determination for different fractions of the range of δ_{CP} and the optimized beam design (right).

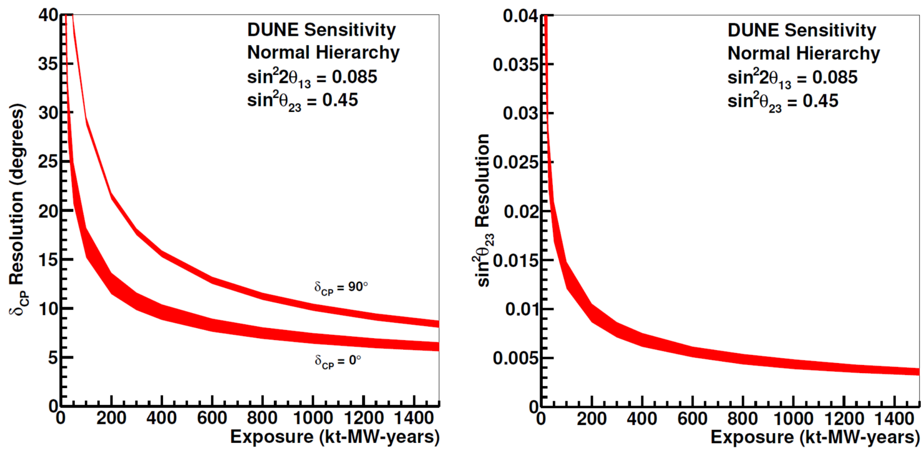

FIG. 6: Resolution for measuring δ_{CP} (left) and $sin^2\theta_{23}$ (right) as a function of exposure.

that is compatible with expectations utilizing the DUNE near detector. The importance of good control of systematic errors is evident, as is the advantage of further beam optimization. With tight systematic errors and the optimized beam, a 5σ discovery of CPV over 50% of the δ_{CP} range requires an exposure of about 500 kt-MW-years.

Sensitivity MH determination is shown for the optimized beam design. This measurement is mainly limited by statistical errors. In the best case, the MH can be determined to $>5\sigma$ with very small exposure, while an exposure of about 250 kt-MW-years is required to cover

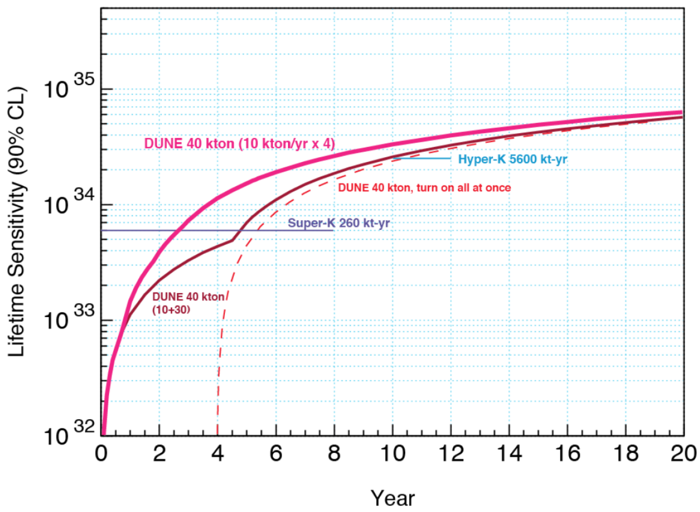

FIG. 7: Expected 90% limit on the lifetime for $p \to K^+\bar{\nu}$ as a function of time for several staging scenarios for the DUNE LAr TPC detector.

the full δ_{CP} range.

Resolutions for measuring δ_{CP} and $sin^2\theta_{23}$ are shown in Fig. 6. The width of the bands shows the sensitivity to different neutrino beam designs. For large exposures the measurement resolution for δ_{CP} is better than 10° and approaches 5° if δ_{CP} is near 0. The asymptotic resolution for $sin^2\theta_{23}$ is less than 0.005.

A unique capability of a LAr TPC is its high detection efficiency and strong background rejection for observing potential nucleon decay modes involving kaons, such as $p \to K^+\bar{\nu}$, which are difficult to observe in water Cherenkov detectors. The signature is an isolated K^+ of the appropriate energy, which can be cleanly identified by its dE/dx pattern and its subsequent decay into easily identified modes such as $K^+ \to \mu^+ \to e^+$ or $K^+ \to \pi^+\pi^0$. The expected detection efficiency is >95% with essentially no background (<0.5 event for a 10 year exposure of a 40 kt detector), allowing a single event to provide evidence for proton decay. The lifetime limit grows essentially linearly with time for many years, as shown in Fig. 7, which also shows the current limit from Super-K[23] and a projected limit for Hyper-K assuming similar efficiencies as Super-K.

The DUNE LAr TPC also provides unique capabilities for the measurement of neutrinos from a core-collapse supernova. It is mainly sensitive to ν_e, through the reaction $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$, while existing water and liquid scintillator detectors are mainly sensitive to $\bar{\nu}_e$ through the inverse beta decay reaction. In addition to providing complemen-

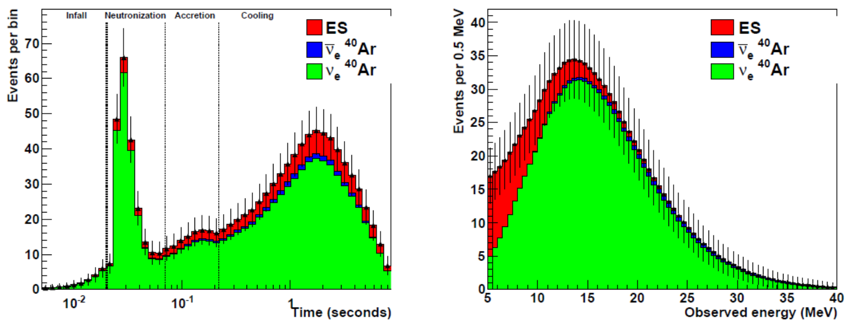

FIG. 8: Expected time-dependent signal in a 40 kt LAr TPC for an electron-capture supernova at 10 kpc (left) and the time-integrated energy spectrum (right).

tary information over the full time-scale of the supernova explosion, DUNE provides a clean measurement of the neutronization burst. Figure 8 shows both the time evolution of the neutrino signal and the time-integrated energy spectrum for an electron-capture supernova[24] computed using SNoWGLoBES[25].

SUMMARY

DUNE has an advanced design for a world-leading experiment focused on fundamental open questions in particle physics and astroparticle physics: long-baseline oscillation physics to determine CPV and MH, make precision measurements of oscillation parameters, test the three-neutrino paradigm, and look for physics beyond the standard model; search for nucleon decay in modes to which current detectors are comparatively insensitive; and neutrino astrophysics, especially measurements of supernova neutrinos. A clear scientific strategy has been established, and the construction project is moving forward with a plan for first data from the far detector in the middle of the next decade.

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