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FUNDAMENTAL RESEARCH CONCEPTS FOR THE DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

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ABSTRACT

This report provides a concise overview of the core conceptual foundations which will be involved in the planned undergraduate physics research project. It encompasses a brief historical account of the strides achieved in neutrino physics and an introduction to the theory of neutrino oscillations. Subsequently, we delve into the specifics of the Deep Underground Neutrino Experiment, offering insights into the detectors, facilities, and detector technology.

1. INTRODUCTION

Neutrino physics is a branch of particle physics that focuses on the study of neutrinos, which are subatomic particles that are extremely difficult to detect due to their weak interactions with matter. Neutrinos are part of the Standard Model (SM) of particle physics and come in three different flavors: electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ). Each flavor of neutrino is associated with a corresponding charged lepton (electron, muon, or tau).

The Deep Underground Neutrino Experiment (DUNE) is a major international neutrino experiment designed to study various aspects of neutrino physics, including neutrino oscillations, neutrino interactions, and the search for proton decay (Abi et al., 2020). DUNE aims to make precise measurements of neutrino properties using a massive liquid argon time-projection chamber (LArTPC) detector, which is located deep underground to shield it from cosmic ray interference.

While DUNE is designed to study all three neutrino flavors, a particular emphasis will be placed on tau neutrinos. Tau neutrinos are the least understood of the three flavors (Abi et al., 2020), and studying their oscillations is crucial for a comprehensive understanding of neutrino physics. In this project, we will have a particular focus on optimizing machine learning algorithms to determine the sensitivity of the far DUNE detector to tau neutrinos.

2. NEUTRINOS

2.1. *A Brief History*

The discovery of neutrinos, a remarkable episode in particle physics history, emerged from decades of experiments and theoretical developments. The concept of neutrinos was introduced by Wolfgang Pauli in the early 1930s to address energy and momentum conservation discrepancies in certain radioactive beta decay processes. Although he famously wagered that neutrinos could never be detected, in 1956, Clyde Cowan and Frederick Reines confirmed their existence through an experiment in South Carolina, USA, where they observed antineutrinos interacting with protons to produce positrons and neutrons.

Subsequently, in the 1960s and 1970s, a shortfall in the expected number of solar neutrinos (electron neutrinos) led to the investigation of what became known as the "solar neutrino problem." Raymond Davis Jr. and John N. Bahcall's experiment in South Dakota, USA contributed to this research by using chlorine atoms to detect solar neutrinos deep underground. The observed deficit compared to predictions and raised questions about neutrino physics and solar processes.

The puzzle was resolved in the late 1900s and early 2000s with the discovery of neutrino oscillations (see Sec. 2.2.2), wherein neutrinos change their flavor as they travel long distances (Nakahata, 2022). The Super-Kamiokande and Sudbury Neutrino Observatory experiments provided critical evidence for these oscillations, fundamentally altering our understanding of neutrinos. The implications of this discovery were far-reaching. It was revealed that neutrinos, previously assumed to be massless, indeed possessed mass (Nakahata, 2022). This realization challenged the established SM of particle physics, prompting the need for significant revisions and extensions to accommodate the newfound knowledge about neutrinos. It also opened new avenues for exploring neutrinos' fundamental properties and their role in the universe.

2.2. *Underlying Neutrino Physics*

2.2.1. *General Properties*

Neutrinos, existing in three flavors — ν_e, ν_μ, and ν_τ — correspond to charged leptons e, μ, and τ respectively. These elusive particles possess distinctive properties. Neutrinos are fermions, characterized by a half-integer spin (specifically 1/2), shared with electrons, quarks, and protons. Unlike other fermions, neutrinos bear no electric charge, leading to minimal electromagnetic interactions and making them challenging to detect (DiBari., 2012).

Their primary interaction occurs through the weak nuclear force, one of nature's fundamental forces, and it's considerably weaker than electromagnetic or strong nuclear forces. Consequently, neutrinos can traverse substantial matter with minimal interaction and can even penetrate the Earth largely undisturbed.

Unveiling precise neutrino mass values and their hierarchy remains a focal point of particle physics research. Although we confirm neutrinos possess mass, it's notably small compared to SM particles like electrons and quarks. Furthermore, the three neutrino flavors exhibit slight differences in estimated mass values.

2.2.2. *Neutrino Oscillations*

Neutrino oscillations are a phenomenon in particle physics that occur when neutrinos change from one flavor to another as they travel through space (Abi et al., 2020). The theory of neutrino oscillations was first proposed by Bruno Pontecorvo, Ziro Maki, Masami Nakagawa, and Shoichi Sakata in the 1960s and was later experimentally confirmed, leading to significant advancements in our understanding of neutrinos and their properties.

Neutrino oscillations arise from the fact that neutrinos are quantum mechanical particles described by wavefunctions, and they have mass. In quantum mechanics, a particle's wavefunction is a superposition of its different mass eigenstates. In the case of neutrinos, these mass eigenstates are different from their flavor eigenstates (Abi et al., 2020). As neutrinos travel through space, they evolve in time, and this evolution is governed by the differences in the masses of the mass eigenstates (Abi et al., 2020). The key to neutrino oscillations is that the flavor eigenstates are not constant during this evolution. Instead, they change as a linear combination of the mass eigenstates, resulting in a periodic oscillation between different neutrino flavors.

The PMNS matrix, also known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, is a mathematical construct used in the field of particle physics to describe the mixing of different types of neutrinos. The PMNS matrix is a 3×3 unitary matrix that describes the relationships between the flavor eigenstates ($|\nu_e\rangle$, $|\nu_\mu\rangle$, and $|\nu_\tau\rangle$) and the mass eigenstates ($|\nu_1\rangle$, $|\nu_2\rangle$, and $|\nu_3\rangle$) of neutrinos (Bellini et al., 2014). In its simplest form, it is expressed as the following unitary transformation:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle . \tag{1}$$

Here, the subscript α indicates flavor eigenstates as $\alpha = e, \mu, \tau$ and the subscript i indicates mass eigenstates, m_i, such that $i = 1, 2, 3$. $U_{\alpha i}$ represents the coefficients of the PMNS matrix (coefficients of the linear combination of mass eigenstates). When the standard three-neutrino theory is considered, the matrix is 3×3. If only two neutrinos are considered, a 2×2 matrix is used. If one or more sterile neutrinos (hypothetical neutrino particles) are added, it is 4×4 or larger (Bellini et al., 2014). In the 3×3 form, it is given as follows:

$$\begin{aligned} U &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} . \end{aligned} \tag{2}$$

Here, c_{ij} and s_{ij} represent $\cos\theta_{ij}$ and $\sin\theta_{ij}$ respectfully, with θ_{ij} representing the mixing angle. The phase factor, δ, is non-zero only if neutrino oscillations violate charge-partity (CP) symmetry (Nunokawa et al., 2008). CP symmetry combines both charge and parity symmetries. It suggests that the laws of physics should be the same if you simultaneously replace all particles with their antiparticles (charge reversal) and invert the spatial coordinates (parity reversal) (Nunokawa et al., 2008). In other words, CP symmetry postulates that the fundamental laws of physics should be invariant under this combined transformation. For neutrinos, we are concerned with if neutrinos and anti-neutrinos oscillate with the same probabilities. Neutrino oscillation experiments have provided strong evidence for the existence of CP violation in the neutrino sector, implying a non-zero value for δ (Abi et al., 2020).

The matrix elements $U_{\alpha i}$ in Eq. 1 and 2 determine the probability amplitudes for a neutrino of a specific flavor eigenstate to be in a specific mass eigenstate (Abi et al., 2020). Eigenstates with different masses propagate at varying frequencies (Bellini et al., 2014). The more massive ones exhibit quicker oscillations when contrasted with their lighter counterparts. Given that mass eigenstates also result from combinations of flavor eigenstates, this difference in oscillation frequencies leads to interference between the corresponding flavor constituents of each mass eigenstate. When constructive interference occurs, it becomes feasible to witness a neutrino, initially of a particular flavor, altering its flavor during its journey. The likelihood of a neutrino, originally of flavor α, ultimately being detected as having flavor β (for the case of two neutrinos) is as follows:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right). \quad (3)$$

Here, Δm_{ij}^2 represents the the mass difference (which is defined as $m_i^2 - m_j^2$), L represents the oscillation distance, and E represents neutrino energies. This formula is commonly employed when analyzing the transition $\nu_\mu \leftrightarrow \nu_\tau$ in atmospheric mixing, as the electron neutrino has minimal involvement in this scenario (Abi et al., 2020). It is also applicable to the solar case $\nu_e \leftrightarrow \nu_\chi$, where ν_χ is a mix/superposition of ν_μ and ν_τ (Abi et al., 2020). These simplifications are possible due to the exceedingly small mixing angle θ_{13} and the close proximity in mass of two of the mass states compared to the third one.

Experiments are able to measure $P(\nu_\alpha \to \nu_\beta)$ and E while L is usually set or known. The focus then becomes calculating θ_{ij} and Δm_{ij}^2 (which I will refer to from now on as Δm^2 unless otherwise required). Determining Δm^2 is especially important because using it we are able to create a mass hierarchy for neutrinos. The neutrino mass hierarchy refers to the relative ordering of the masses of the three known flavors of neutrinos. Experiments involving neutrino oscillations have provided important insights into their masses and their mass hierarchy. There are two possible neutrino mass hierarchies: the normal hierarchy (NH) and the inverted hierarchy (IH). In the NH, the mass ordering of neutrinos is as follows: the lightest neutrino is ν_1, the next heaviest is ν_2, and the heaviest is ν_3 (Qian & Vogel, 2015). This hierarchy is also sometimes referred to as the "1-2-3 hierarchy." In the IH, the mass ordering is as follows: the lightest neutrino is ν_3, the next heaviest is ν_1, and the heaviest is ν_2 (Qian & Vogel, 2015). This hierarchy is also sometimes referred to as the "3-1-2 hierarchy."

Experimental efforts, such as those conducted at neutrino observatories and particle physics facilities, have been dedicated to measuring the neutrino mass hierarchy. By carefully measuring the oscillation patterns and the differences in masses, scientists have made significant progress in determining the neutrino mass hierarchy, although it remains an active area of research. The precise determination of the neutrino mass hierarchy can help us refine our understanding of the SM of particle physics and may have implications for theories beyond the SM, such as those related to dark matter and the nature of the universe's earliest moments.

3. DUNE

The dominance of matter over antimatter in the early universe, the intricate behaviors of supernova neutrino bursts (SNBs) responsible for creating the vital elements for life, and the possibility of proton decay are all mysteries central to the forefront of particle physics and astrophysics. These puzzles are essential for gaining insights into the initial development of our universe, its present condition, and its ultimate destiny. DUNE stands as a world-class international experiment committed to unraveling these mysteries.

The DUNE experiment is made up of three central elements: a state-of-the-art high-intensity neutrino source produced by a proton accelerator at Fermilab, delivering megawatt-class power, a far detector (FD) positioned 1.5km underground at the Sanford Underground Research Facility (SURF) in South Dakota, and a composite near detector (ND) strategically installed just ahead of the neutrino source (Abi et al., 2020) (see Fig. 1). The Long Baseline Neutrino Facility (LBNF) project, hosted by Fermilab, will provide the beamline and the civil construction for both detectors of the DUNE experiment.

3.1. *The Dune Detectors*

3.1.1. *The Near Detector*

Although project work will focus more on the FD, it is still essential to highlight the pivotal role of the ND in the experiment. The ND plays a fundamental part by serving as the experiment's control, effectively constraining systematic errors and measuring the initial, unaltered energy spectra of ν_e and ν_μ (and their antineutrinos) (Hewes et al., 2021). This comparison of energy spectra near the beam source, before any oscillation occurs, and at the far site is crucial for untangling the various energy-dependent effects that influence the beam spectrum. It also helps to diminish systematic uncertainties to the extent necessary for the detection of CP violation (Hewes et al., 2021). Furthermore, the ND plays a significant role in precisely measuring neutrino-argon interactions using both gaseous and liquid argon (Hewes et al., 2021). This measurement further mitigates the systematic uncertainties associated with modeling these interactions, enhancing the accuracy of the experiment.

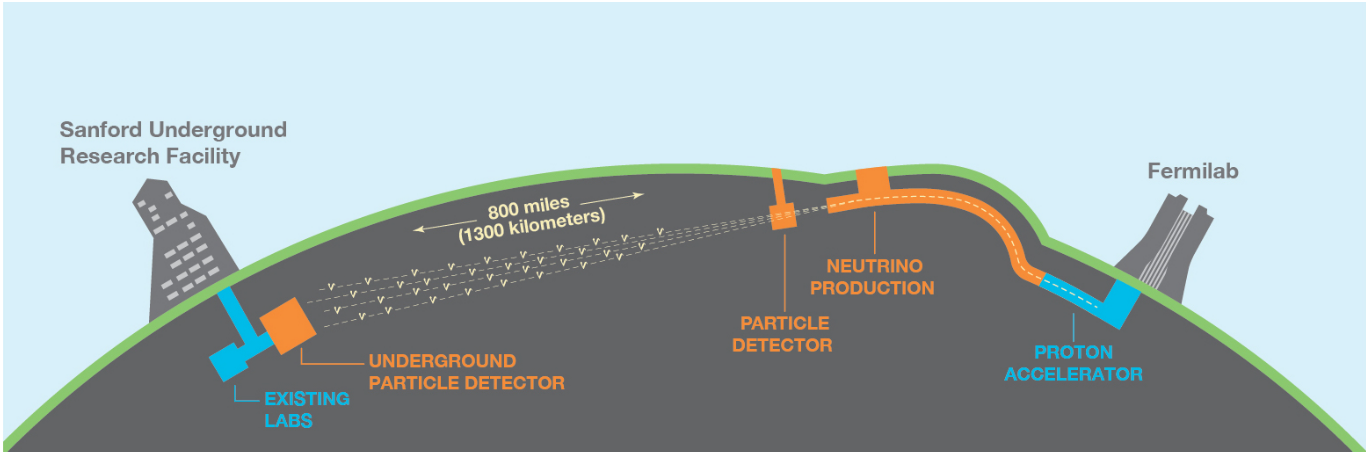

Figure 1. The configuration of the LBNF beamline at Fermilab, Illinois, and the DUNE detectors in Illinois and South Dakota, separated by 1300 km. (source: dunescience.org)

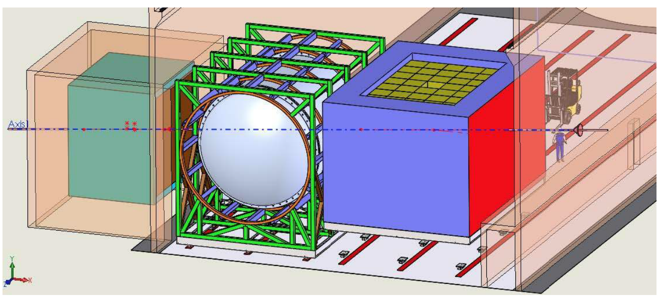

Figure 2. A setup of the DUNE ND. The beam is shown as it enters from the right. Neutrinos first encounter the LArTPC (right), the MPD (center), and then the on-axis beam monitor (left). (source: (Abi et al., 2020))

Furthermore, the ND will have its own distinct physics program, separate from the FD. This program encompasses the measurement of neutrino interactions, delving into two fundamental aspects of the SM: electroweak physics and quantum chromodynamics (Hewes et al., 2021). In addition, it will embark on explorations beyond the SM, actively seeking non-standard interactions, sterile neutrinos, dark photons, and other exotic particles (Abi et al., 2020). Positioned 574m downstream from the neutrino beam source, the ND will consist of three primary detector components: a LArTPC called ArgonCube, a high-pressure gaseous argon Time Projection Chamber (HPgTPC), surrounded by an electromagnetic calorimeter (ECAL) collectively referred to as the multi-purpose detector (MPD), and a on-axis beam monitor called System for on-Axis Neutrino Detection (SAND) (Abi et al., 2020) (see Fig. 2).

3.1.2. *The Far Detector*

The DUNE FD comprises four LArTPC detector modules, each housing a minimum of 10 kt of liquid argon within the cryostat's sensitive area, situated approximately 1.5 km below the surface (Abi et al., 2020). The design of the four equally sized modules is adaptable enough to accommodate staged construction and the ongoing evolution of LArTPC technology (see Fig. 3). DUNE is currently planning and developing two LArTPC technologies: single-phase (SP), where all detector components inside the cryostat are submerged in liquid, and dual-phase (DP), where certain elements function within a layer of gaseous argon above the liquid.

- Within the SP technology, ionization charges traverse the liquid argon (LAr) horizontally, guided by an electric field (E field) towards a vertical anode for subsequent readout (Abi et al., 2020). This configuration mandates the use of exceptionally low-noise electronics to achieve effective readout with a favorable signal-to-noise (S/N) ratio, as there is no in-cryostat signal amplification (see Fig. 4).

- DP technology is not as well-established as the SP technology, and although it comes with some challenges, it offers several benefits. In DP, ionization charges ascend vertically within the liquid argon and then transition into a layer of gaseous argon above the liquid (Abi et al., 2020). Special devices known as large electron multipliers (LEMs) amplify these signal charges in the gas phase before they reach a horizontal anode. This amplification in the gas phase reduces the requirements on electronics noise and allows for an extended drift length, which, in turn, necessitates a higher voltage (see Fig. 5).

Argon, being an excellent scintillator at a wavelength of 126.8 nm (ultraviolet or UV) (Abi et al., 2020), is a

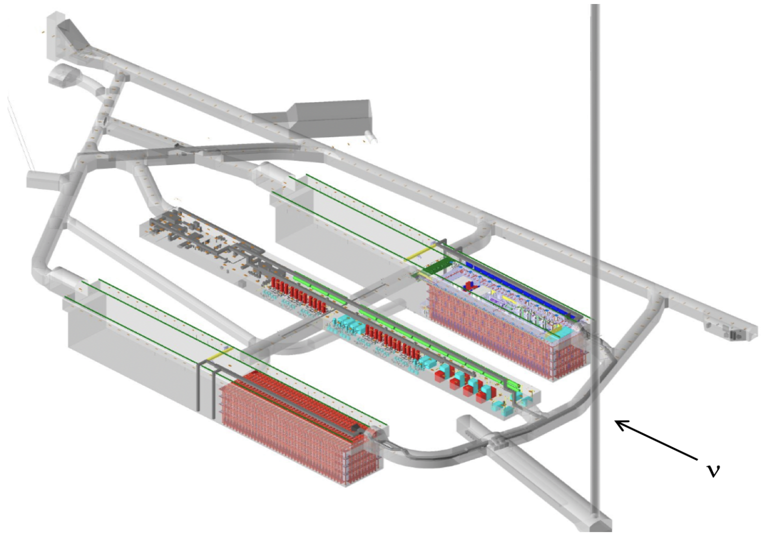

Figure 3. At SURF in South Dakota, underground chambers have been prepared to house the DUNE FD and its associated cryogenics systems. In the illustration, you can see the cryostats (red), which are designated for the initial two FD modules. On the right-hand side, the Ross Shaft, a vertical passage, will serve as the entry point to the subterranean area dedicated to DUNE. Each cryostat has dimensions of 65.8m in length, 18.9m in width, and 17.8m in height. The two detector caverns, accommodating these cryostats, measure 144.5m in length, 19.8m in width, and have a height of 28.0m, offering additional space around the cryostats. (source: (Abi et al., 2020))

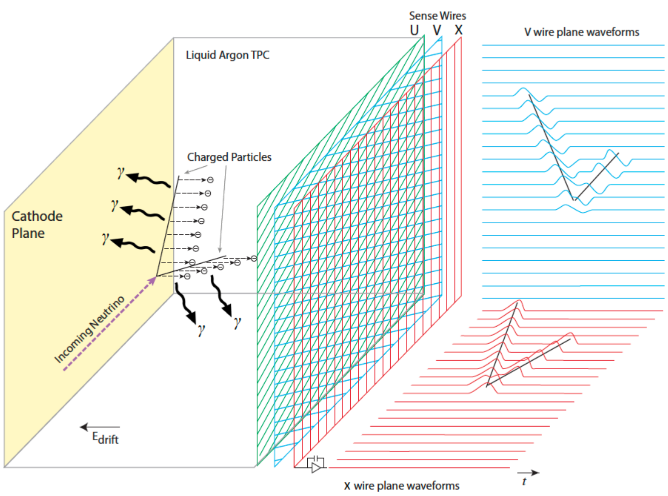

Figure 4. The operational concept of the SP LArTPC involves the migration of negatively charged ionization electrons generated by a neutrino interaction. These electrons drift horizontally, opposite to the E field, within the LAr and accumulate on the anode, composed of U, V, and X sense wires. On the right-hand side, a depiction illustrates the two-dimensional time projections as the event unfolds. The timing of the interaction's occurrence is determined by light detectors (not depicted), providing the event's t_0. (source: (Abi et al., 2020))

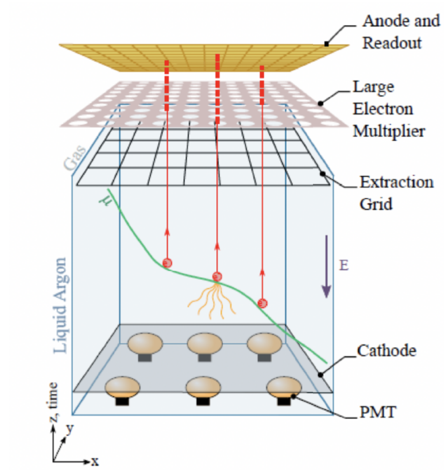

Figure 5. The fundamental concept behind the DP LArTPC is as follows: ionization charges ascend vertically within the LAr and then transition into a layer of argon gas above the liquid, where they undergo amplification before being gathered on the anode. Positioned beneath the cathode are the light detectors, known as photomultiplier tubes (PMTs). (source: (Abi et al., 2020))

feature harnessed by both detector designs. The emission of scintillation light in the form of photons is subsequently converted into the visible spectrum and captured by photon detectors (PDs) in both systems. This light collection provides an initial event start time (t_0) for every occurrence registered by the time projection chamber (TPC), signifying the commencement of ionization electron drift (Abi et al., 2020).

4. CONCLUSION

The creation of algorithms and software infrastructure necessary for conducting physics sensitivity studies has been a dynamic endeavor within both DUNE and the affiliated scientific community. Substantial headway has been achieved, enabling event reconstruction codes to be applied to entirely simulated neutrino interaction events occurring within DUNE FD modules. In the context of the long-baseline oscillation physics program, this approach demands a comprehensive analysis of fully simulated FD data alongside a concurrent evaluation of simulated data from ND systems to realistically account for systematic error control.

Through a single groundbreaking experiment, DUNE will provide an extensive examination of the three-flavor model of neutrino physics with an unprecedented level of precision. Its most prominent potential breakthrough lies in the detection of matter-antimatter discrepancies, achieved through the investigation of CP symmetry violation in neutrino flavor mixing—a significant stride towards uncovering the mystery of matter formation in the early universe. Additionally, DUNE's determination of the neutrino mass hierarchy and its precise measurement of neutrino mixing parameters could potentially unveil fundamental symmetries of nature.

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