Long Baseline Neutrino Facility

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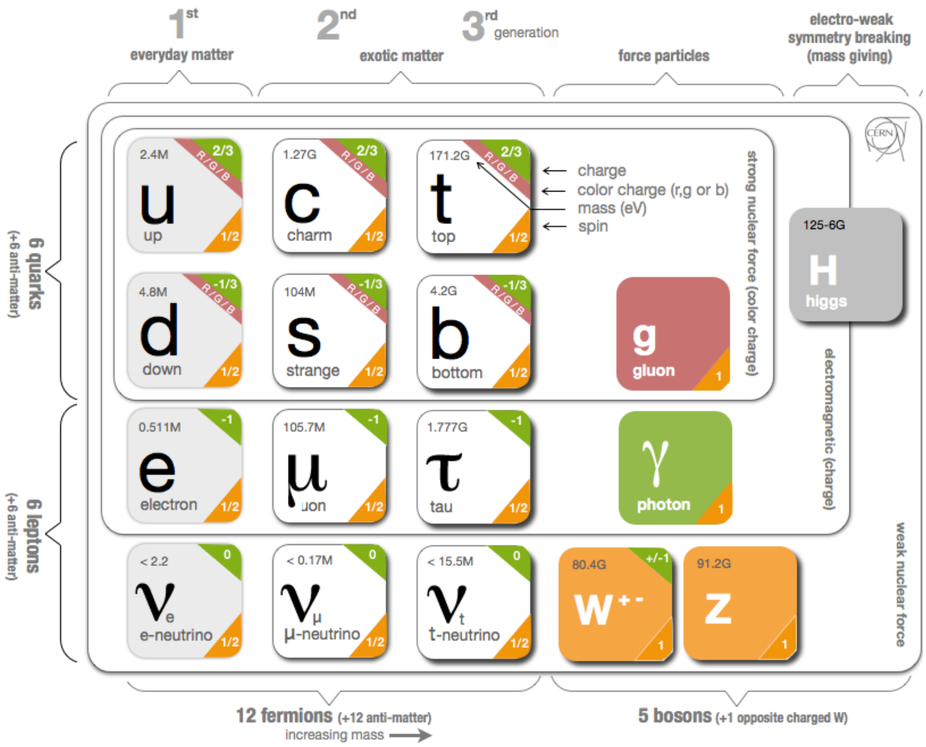
Abstract

This paper reviews the physics program and experimental setup of the future LBNF/DUNE experiment. This is the most ambitious experiment in the world, to date, for studying neutrino oscillations. General properties of neutrinos, theoretical and historical backgrounds of the oscillations, techniques and achievements of several other experiments are also discussed. This paper is prepared as a part of the author's Comprehensive Exam at the Department of Physics&Astronomy at the University of Nebraska-Lincoln.

Contents

Figure 1: Fundamental particles and their interactions according to the Standard Model. There exist three generations of fermions. Fermions interact through the exchange of Gauge Bosons. Charged leptons and quarks (fermions) are subject to electromagnetic interactions (through photons). Quarks also interact strongly (through gluons). All leptons and quarks interact weakly (through $W^{\pm}$ and Z^0 bosons). All of the fundamental particles of the Standard Model have been discovered, and nothing more. Source of picture: [1]



1 Introduction. Neutrinos as Fundamental Standard Model Particles

The Standard Model can be summarized in the table in Fig. 1. It includes three charged leptons, three neutrinos, six quarks and their antiparticles, which are split into three generations. In addition, it includes the gauge bosons, the Higgs boson and three fundamental interactions: electromagnetic, strong and weak. Charged particles, which include three leptons (electrons, muons and τ-leptons), all quarks, W bosons and their antiparticles can interact electromagnetically, through exchange of virtual photon. Quarks have non-integer electric charges (in units of absolute value of the electron charge) of +2/3 or -1/3. They also possess an additional quantum number which is called “color” and can participate in strong couplings, through exchange of gluons. Individual quarks do not exist in nature, they are present in combinations of three quarks

Figure 2: Feynman diagrams of neutral current (NC, left), and charged current (CC, middle and right) neutrino interactions.

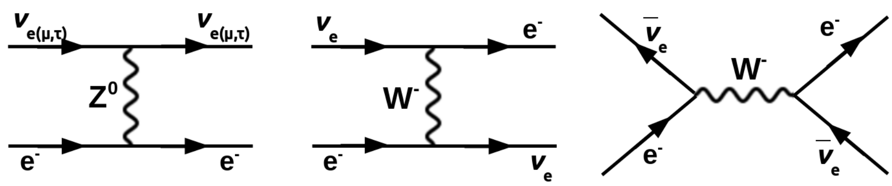


Figure 3: Feynman diagrams of (left) neutron and (right) muon decays. Neutron beta decay is a d-quark transforming into u-quark through the W boson emission of an electron and an electron antineutrino. A muon decays into an electron, a muon neutrino and an electron antineutrino through a W boson.

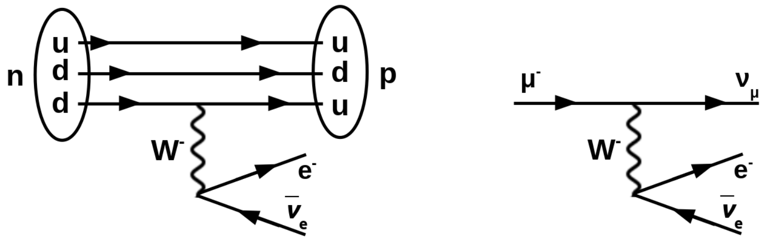


Figure 4: Cosmic shower induced by scattering of the incident cosmic proton off an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$.

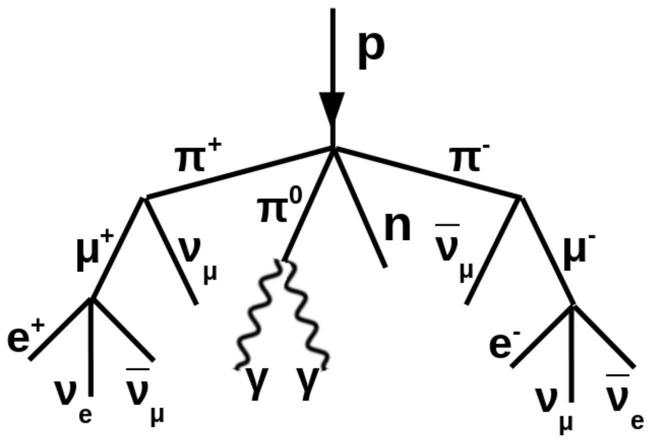


Table 1: Lepton Flavor Number

particles	L_e	L_μ	L_τ
e^-, ν_e	+1	0	0
$e^+, \bar{\nu_e}$	-1	0	0
μ^-, ν_μ	0	+1	0
$\mu^+, \bar{\nu_\mu}$	0	-1	0
τ^-, ν_τ	0	0	+1
$\tau^+, \bar{\nu_\tau}$	0	0	-1

or quark-antiquark pairs. Particles composed of three quarks are called baryons, and particles composed of quark and antiquark are called mesons. Baryons and mesons are always neutral in color, and possess integer electric charge. All baryons and mesons are called hadrons.

All of these particles and also neutrinos can interact through weak interactions, through charged current (CC), by exchanging a W boson, and through neutral current (NC), by exchanging a Z boson. The corresponding Feynman diagrams for NC and CC are shown in Fig. 2. The left Feynman diagram shows an electron scattering off a neutrino through NC. Any neutrino or antineutrino can scatter off an electron with NC. Moreover, any weakly interacting particle can scatter off any other weakly interacting particle through NC because Z^0 does not transform a particle into any other particle, but is just emitted from the fermion line. The middle Feynman diagram in Fig. 2 shows $e^-\nu_e \rightarrow e^-\nu_e$ scattering through CC. The W boson transforms the neutrino into a corresponding charged lepton or vice-verse and therefore only $f^-\nu_f \rightarrow f^-\nu_f$ scattering is possible with CC where f is e, μ or τ. For example, $e^-\nu_\mu \rightarrow e^-\nu_\mu$ scattering is possible through NC only. The right Feynman diagram shows the process of $e^-\bar{\nu_e}$ annihilation with further production of $e^-\bar{\nu_e}$. In principle, any $f^-\bar{\nu_f}$ or $f^+\nu_f$ pair could get produced from decay of a virtual W boson.

All known substances in the known Universe consist of millions of different species of molecules which are composed of hundreds of different species of atoms. Each atom consists of a certain number of protons, neutrons and electrons. All protons and neutrons are composed of three quarks (uud for the proton and udd for the neutron) which are glued together by strong interactions. Therefore, all known substance consists of only the three fundamental particles from Fig. 1: u- and d-quarks and electrons. Despite the fact that neutrinos are not a part of substances, a large number of them exist in nature without any human-built machines. Quoting [2], 11.1: "John Bahcall, who was responsible for most of the calculations of solar neutrino abundances, liked to say that 100 billion neutrinos pass through your thumbnail every second; and yet they are so ethereal that you can look forward to only one or two neutrino-induced reaction in your body during your entire lifetime".

Two very common and well known interactions with neutrino participation are neutron beta decay and muon decay. The Feynman diagrams of these processes are shown in Fig. 3. The mean lifetime of a free neutron is $\sim$15 minutes and it decays as $n \rightarrow p + e^- + \bar{\nu_e}$ [3]. At the level of fundamental particles, neutrons consist of two d-quarks and one u-quark and in the beta decay one of the d-quarks transforms into a u-quark through the weak interaction mediated by a W^- boson. Thus, the proton, which consists of two u-quarks and one d-quark, is being produced from neutron beta decay. When this happens, an electron and an electron antineutrino are emitted to conserve the charge and lepton flavor number. Examples of the neutron beta decay in nature include ${}^{49}{}_{19}K \rightarrow {}^{40}{}_{20}Ca$, ${}^{64}{}_{29}Cu \rightarrow {}^{64}{}_{30}Zn$, ${}^{3}{}_{1}H \rightarrow {}^{3}{}_{2}He$ [2] (the positive beta decay, $p \rightarrow n + e^+ + \nu_e$, is forbidden for a free proton by energy conservation but it is allowed in certain cases when a proton is part of a nuclei). Such reactions are widely used for neutrino and antineutrino detection.

As for a muon, its mean lifetime is $2\mu s$, and it decays as $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu_e}$ through the

W boson. This process is also common in nature in cosmic rays as shown in Fig. 4. Highly energetic cosmic protons scatter off the atmosphere molecules, for instance, as $p+p \rightarrow n+p+\pi^+$, $p+n \rightarrow n+n+\pi^-$ and $p+p \rightarrow p+p+\pi^0$. Several additional hadrons can be produced in the reaction. If π^0 is produced, it decays to two photons as $\pi^0 \rightarrow \gamma\gamma$. Charged pions decay as $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu_\mu})$ and then some number of muons decay as $\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu_e}) + \bar{\nu_\mu}(\nu_\mu)$ while traveling through the atmosphere to the ground. A Feynman diagram of muon decay is shown in Fig. 3. The muon transforms into muon neutrino with emission of a W boson, then the W boson decays into an electron and an electron antineutrino.

There are three flavors of neutrinos, one for each generation: an electron neutrino, a muon neutrino and a τ-neutrino. In the processes described above (neutron beta decay and muon decay) the lepton flavor numbers L_e, L_μ and L_τ are conserved. Table 1 shows the value of this number for all leptons and anti-leptons.

Lepton flavor number is conserved in almost all particle physics processes and the only violation of this law ever observed is through neutrino oscillations: the ability of a neutrino to change flavor.

This paper is about neutrino oscillations. Chapter 2 of this paper reviews the theoretical background of neutrino oscillations starting from a simplified two-neutrino model in vacuum to a three-neutrino model in the presence of matter; and also discusses possible mechanisms to give neutrinos mass. Chapter 3 gives a historical background of related experimental measurements including the first evidence of neutrino oscillations, and milestones achieved by the scientific community in measuring different neutrino oscillation parameters including the most recent experimental results. Chapter 4 explains the need of a new experiment and gives an overview of the proposed LBNF/DUNE experiment in terms of its physics program and experimental setup. It also discusses the advantages of LBNF/DUNE by comparison of the other experiments of this kind. Chapter 5 draws conclusions on the potential scientific impact of the proposed LBNF/DUNE project.

2 Neutrino Oscillations. Theory

Consider a simplified model of two-neutrino oscillations in vacuum as it is described in [2], chapter 11. Suppose there are only two neutrinos: ν_e and ν_μ. Then energy eigenstates of the system would be the orthogonal combinations of neutrino flavor eigenstates:

$$\nu_1 = \nu_\mu cos\theta - \nu_e sin\theta,$$
$$\nu_2 = \nu_\mu sin\theta + \nu_e cos\theta.$$

Then, according to the quantum mechanics:

$$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1t}{\hbar}},\ \nu_2(t) = \nu_2(0)e^{\frac{-iE_2t}{\hbar}}.$$

Suppose $\nu_e(t=0) = 1$, $\nu_\mu(t=0) = 0$. Then:

$$\nu_1(0) = -sin\theta,\ \nu_2(0) = cos\theta,$$
$$\nu_1(t) = -sin\theta e^{\frac{-iE_1t}{\hbar}},\ \nu_2(t) = cos\theta e^{\frac{-iE_2t}{\hbar}}.$$

Thus, we obtain the system:

$$-sin\theta e^{-\frac{iE_1t}{\hbar}} = \nu_\mu(t)cos\theta - \nu_e(t)sin\theta,$$
$$cos\theta e^{-\frac{iE_2t}{\hbar}} = \nu_\mu(t)sin\theta + \nu_e(t)cos\theta.$$

By solving this system for ν_e and ν_μ, one obtains:

$$P_{\nu_e\rightarrow\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2\hbar}]^2, \tag{1}$$

$$P_{\nu_e\rightarrow\nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1-E_2)t}{2\hbar}]^2. \tag{2}$$

According to Formulas 1 and 2, for freely traveling neutrinos, if ν_e was emitted, at any point there is a certain probability to register ν_e or ν_μ, and those probabilities change with time periodically, according to the $[sin(At)]^2$ law. That is why the phenomenon is called the neutrino oscillations. Suppose momenta $p_1 = p_2$. Then using $E^2 = p^2 + m^2$ and assuming $m_{1,2} \ll E_{1,2}$, the probabilities will take forms of:

$$P_{\nu_e\rightarrow\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2\hbar}]^2 = [sin2\theta sin\frac{(m_1^2-m_2^2)c^3}{4\hbar E}z]^2, \tag{3}$$

$$P_{\nu_e\rightarrow\nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(m_1^2-m_2^2)c^3}{4\hbar E}z]^2. \tag{4}$$

Therefore, for neutrino oscillations to be present in the two-neutrino system, neutrino mixing must be present ($\theta \neq 0$), and at least one of two neutrinos must be massive, satisfying $m_2 \neq m_1$.

Neutrinos were believed to be massless for a long time, and the simplified weak interactions theory introduces Lagrangian with massless neutrinos [2]. Experiments for direct neutrino mass measurements were only able to set upper limits on the neutrino masses. However, the neutrino oscillations were experimentally observed and therefore at least two out of three neutrinos must be massive.

There are two the most commonly discussed mechanisms of giving neutrinos mass in the Standard Model: one assumes neutrinos to be Dirac particles ($\nu \neq \bar{\nu}$), and the other one assumes neutrinos to be Majorana particles ($\nu = \bar{\nu}$) [3], [4]. If the neutrinos are Dirac, both left-handed and right-handed neutrinos must be present in the Standard Model Lagrangian, but the right-handed neutrino term would be significantly suppressed. Only left-handed neutrinos have been experimentally observed to date which is consistent with an assumption that right-handed neutrinos can participate in weak interactions but with a much smaller probability than left-handed neutrinos. If the neutrinos are Majorana, there is no need for the right-handed neutrino term in the Lagrangian. Majorana neutrinos would mean that there is no lepton flavor number conservation, but lepton flavor number has been observed to be conserved in all phenomena except neutrino oscillations.

In the remaining portion of this chapter we consider the three-neutrino mixing matrix and $P_{\nu_\mu \to \nu_e}$ in the presence of three neutrinos in the Dirac neutrino case.

Three-neutrino case is described in [4] and [5]. For three-neutrino case, the oscillations are determined by a complex unitary matrix which is called Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

An arbitrary 3x3 unitary matrix can be parametrized by 9 parameters, but 5 of them can be absorbed as Dirac phases which do not change the physical properties of the system and therefore the U_{PMNS} matrix can be parametrized with three neutrino mixing angles (θ_{12}, θ_{23}, θ_{13}) and one complex phase δ. If we define $c_{ab} = cos\theta_{ab}$, $s_{ab} = sin\theta_{ab}$, the U_{PMNS} matrix can be split into three multipliers:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Probability $P_{\nu_\mu \to \nu_e}$ in three-neutrino model in vacuum is given by Formula 5 ([4]):

$$P_{\nu_\mu \to \nu_e} \simeq P_1 + P_2 + P_3, \tag{5}$$

$$P_1 = sin^2\theta_{23} \cdot sin^2 2\theta_{13} \cdot sin^2\Delta_{13}, \tag{6}$$

$$P_2 = sin2\theta_{23} \cdot sin2\theta_{13} \cdot sin2\theta_{12} \cdot sin\Delta_{31} \cdot \Delta_{21} \cdot cos(\Delta_{32} + \delta), \tag{7}$$

$$P_3 = cos^2\theta_{23} \cdot cos^2\theta_{31} \cdot sin^2 2\theta_{12} \cdot \Delta_{21}^2, \tag{8}$$

where $\Delta_{ij} = \Delta m_{ij}^2 L/4E$, E is a neutrino energy, and L is a distance traveled by neutrino after being produced (a baseline).

Therefore, $P_{\nu_\mu \to \nu_e}$ depends on the U_{PMNS} parameters, and the differences of squares of neutrino masses. There are two independent expressions for squares of the mass differences: $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$. The mixing angles θ_{12}, θ_{23}, θ_{13} have been measured experimentally, and give the U_{PMNS} matrix a form of:

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.5 & 0.6 & 0.6 \\ 0.2 & 0.6 & 0.8 \end{pmatrix}.$$

The phase δ is unknown.

The analogous matrix for quark mixing, Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{CKM}, is much more diagonal:

$$|V_{CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}.$$

One important question in modern particle physics is why the quark mixing angles are so much smaller than neutrino mixing angles, and whether there is any relationship between quark and neutrino mixing matrices.

Overall, precision measurements of neutrino mixing parameters can bring an insight into understanding of fundamental particle physics questions.

Wave functions of particles and antiparticles are complex conjugates to each other, and a presence of the non-zero complex phase δ in the mixing matrix would mean different behavior for $\nu_\mu \to \nu_e$ and $\bar{\nu_\mu} \to \bar{\nu_e}$ systems. If $\delta \neq 0$ then charge-spacial parity (CP) violation is present in the neutrino system. Because the U_{PMNS} mixing matrix involves CP-violating phase, the studies of neutrino oscillations could provide a hint into the origin of matter-antimatter asymmetry in the Universe. When the Universe was created after the Big Bang, there was supposed to be equal amount of matter and antimatter. Then most of matter and antimatter annihilated, and the tiny excess of matter created the whole Universe which we have today. One possible explanation of an origin of this tiny excess is CP-violation. It is experimentally known that electromagnetic and strong interactions conserve CP, and it only can be violated in the weak interactions. CP-violation in the quark sector has been observed experimentally, and it can also present in the lepton sector due to δ phase in the neutrino mixing matrix. But neutrino oscillation experiments performed before were not sensitive enough to measure δ.

Precision measurements of the parameters of the U_{PMNS} matrix and comparing it to the V_{CKM} matrix may help understanding whether there is any relationship between quark and neutrino mixing. One especially interesting parameter of the U_{PMNS} matrix is angle θ_{23}. According to currently available experimental results, it is indistinguishable from $45^0 (sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$ [3]). If $\theta_{23} = 45^0$ exactly, it might be an indication of a new, unknown symmetry.

Mass differences were measured in other neutrino oscillation experiments, but Δm^2_{21} and Δm^2_{32} are present in Formula 5 evenly and therefore neutrino oscillations in vacuum are not sensitive to the signs of these expressions. Ordering of neutrino masses is called mass hierarchy (MH). Determining mass hierarchy can bring an insight into understanding the flavor symmetry. All the higher generation quarks and charged leptons have higher masses than corresponding lower generation particles (Fig. 1), and only ordering of neutrino masses is not known. If the neutrino MH will be found to be $m_3 > m_2 > m_1$, that would mean that masses of all the fundamental particles order the same way from generation to generation.
$P_{\nu_\mu \to \nu_e}$ in presence of matter assuming it has constant density is described by Formula 9 [4]:

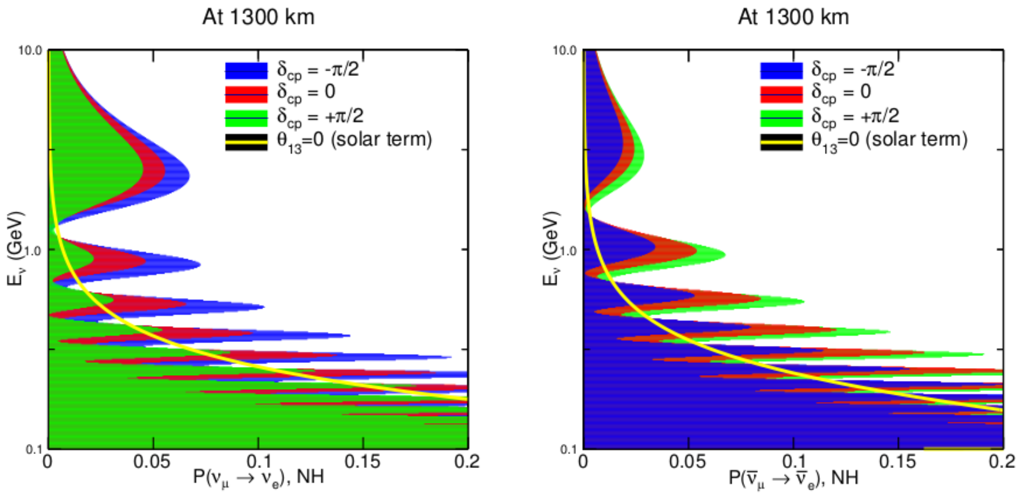
$$P_{\nu_\mu \to \nu_e} \simeq P_1 + P_2 + P_3, \tag{9}$$

$$P_1 = sin^2\theta_{23} \cdot sin^2 2\theta_{13} \cdot \frac{sin^2(\Delta_{13} - aL)}{(\Delta_{13} - aL)^2} \cdot \Delta^2_{31}, \tag{10}$$

$$P_2 = sin2\theta_{23} \cdot sin2\theta_{13} \cdot sin2\theta_{12} \cdot \frac{sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cdot \Delta_{31} \cdot \frac{sin(aL)}{aL} \Delta_{21} \cdot cos(\Delta_{31} + \delta), \tag{11}$$

$$P_3 = cos^2\theta_{23} \cdot sin^2 2\theta_{12} \cdot \frac{sin^2(aL)}{(aL)^2} \cdot \Delta^2_{21}, \tag{12}$$

Figure 5: $P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy. Left: neutrinos, right: antineutrinos. Source of figure: [5].



where $a = G_F N_e/\sqrt{2}$, G_F is the Fermi constant, N_e is a number density of electrons in the Earth's matter, and L is a baseline.

For $P(\bar{\nu_\mu} \to \bar{\nu_e})$ one would need to change $\delta \to -\delta$ and $a \to -a$ [4]. The $a \to -a$ effect introduces sensitivity to MH, and increases with L. It was determined that $m_2 > m_1$ however the sign of Δm^2_{32} is unknown. If the masses order as $m_3 > m_2 > m_1$ it is called normal neutrino mass hierarchy (NH), and if the masses order as $m_2 > m_1 > m_3$ it is called inverted neutrino mass hierarchy (IH).

Fig. 5 shows $P_{\nu_\mu \to \nu_e}$ at a baseline of L=1300 km. Magnitude and frequency of oscillations both depend on δ, and the differences become more significant for higher oscillation nodes which correspond to lower neutrino/antineutrino energies. Changes due to different values of δ are opposite for neutrinos and antineutrinos.

3 Neutrino Oscillations. History and Status

The history of the discovery of neutrino oscillations is described in [2], chapter 11. The first evidence of neutrino oscillations was seen in the Homestake experiment in 1968 with solar neutrinos. This experiment used a Chlorino radiochemical detector. Neutrinos interacted with chlorine-37 atoms and converted them to argon-37 through the reaction $\nu_e +^{37} Cl \rightarrow^{37} Ar + e$ or, at the more fundamental level, $\nu_e + n \rightarrow p + e$. The argon atoms were then separated and counted. The experiment registered a number of neutrinos three times smaller than theoretically predicted. The phenomenon was called the "solar neutrino problem". The detector was sensitive to electron neutrinos only. Soon after Bruno Pontecorvo proposed the explanation to the solar neutrino problem that neutrino can change its flavor on its way from the Sun to the detector. The theory was confirmed by Super-Kamiokande and Sudbury Neutrino Observatory (SNO) collaborations.

The Super-Kamiokande experiment used a water detector and could register any sort of neutrino through $e + \nu \rightarrow e + \nu$ scattering. However the NC scattering can not distinguish between different neutrino flavors. Also, electron neutrinos could interact through CC, which made the detection efficiency of electron neutrinos 6.5 times higher than other flavors (the left Feynman diagram in Fig. 2 is possible for any neutrino flavor but the middle diagram is possible only for electron neutrino). Therefore, Super-Kamiokande was able to register any neutrino but could not distinguish between neutrino flavor and had lower detection efficiency for non-electron neutrinos. They assumed all neutrinos to be electron neutrinos and recorded 45% of the predicted amount. Then the SNO, which used heavy water and was able to distinguish the electron neutrino flux from the total neutrino flux, confirmed that some of the neutrinos coming from the Sun are detected as ν_μ or ν_τ. The reactions in the working volumes of the three detectors can be summarized as the following:

- Homestake experiment (1968): $\nu_e +^{37} Cl \rightarrow^{37} Ar + e$
- Super-Kamiokande experiment (1998): $\nu + e \rightarrow \nu + e$
- Solar neutrino observatory (2002): $\nu_e + d \rightarrow p + p + e$, $\nu + d \rightarrow n + p + \nu$, $\nu + e \rightarrow \nu + e$

The SNO reported ν_e flux to be 35% of the predicted flux. Comparing it to the Super-Kamiokande results and knowing that Super-Kamiokande was 6.5 times less sensitive to ν_μ and ν_τ, one obtains:

$N_{SNO} = 0.35 \cdot N_{th}$,

$N_{SK}^{CORR1} = 0.45 \cdot N_{th} = 0.35 \cdot N_{th} + 0.1 \cdot N_{th}$,

$N_{SK}^{CORR1} = \frac{N_{SK}^{REG}}{\epsilon^e} = 0.45 \cdot N_{th}$,

$N_{SK}^{CORR2} = \alpha \cdot \frac{N_{SK}^{REG}}{\epsilon^e} + (1-\alpha) \cdot \frac{N_{SK}^{REG}}{\epsilon^{\mu/\tau}} = \alpha \cdot \frac{N_{SK}^{REG}}{\epsilon^e} + (1-\alpha) \cdot \frac{N_{SK}^{REG}}{\epsilon^e/6.5}$,

$\alpha = 0.35/0.45$,

$N_{SK}^{CORR2} = 0.35 \cdot N_{th} + 0.65 \cdot N_{th} = N_{th}$,

where N_{th} is a number of theoretically predicted neutrinos, N_{SNO} is a number of neutrinos registered by the SNO experiment corrected by the neutrino detection efficiency, N_{SK}^{REG} is a number of neutrinos registered by Super-Kamiokande, N_{SK}^{CORR1} is a number of neutrinos registered by Super-Kamiokande corrected by the electron detection efficiency, ϵ^e is the electron detection efficiency, N_{SK}^{CORR2} is a number of neutrinos registered by Super-Kamiokande corrected in assumption that part of registered neutrinos were ν_e and the other part were ν_μ or ν_τ. This result confirmed the neutrino oscillations theory and resolved the solar neutrino problem.

There are four types of experiments which allow to study neutrino properties: solar, atmospheric, reactor, and accelerator neutrino experiments [3]. The idea of any neutrino oscillation measurement is to observe and quantify disappearance of $\nu_f(\bar{\nu_f})$ and/or appearance of $\nu_{f'}(\bar{\nu_{f'}})$, where f is a flavor of neutrinos produced in the reaction in the Sun, atmosphere, reactor or target, and f' is the flavor of neutrinos which were not produced in the reaction.

The Sun is a source of electron neutrinos. They are produced in the reaction $4p \to {}^4He + 2e^+ + 2\nu_e$. Solar neutrino experiments (as the three described above) focus on the disappearance of ν_e and appearance of ν_μ or ν_τ. These experiments are characterized by very long baselines (distance from the Sun to the Earth, $\simeq 1.5 \cdot 10^8$ km) and neutrino energies of ~ 1 MeV. Solar neutrino experiments are sensitive to $\Delta m^2_{21} = \Delta m^2_{Sol}$, which is also called Solar mass splitting. Matter effects in the Sun makes such experiments sensitive to the sign of Δm^2_{21}, and it was determined that $m2 > m1$ [6]. The Solar neutrino experiments also provided the first measurements of the mixing angle θ_{12}.

The nuclear reactors produce $\bar{\nu_e}$s in beta decay of radioactive elements as $n \to p + e^- + \bar{\nu_e}$, and then antineutrinos further oscillate and are detected. Typical baselines of such experiments vary from 1 to 100 km, and the energies of emitted antineutrinos are ~ 1 MeV. Reactor experiments provide measurements of Δm^2_{21}, θ_{12} and θ_{13}.

The source of atmospheric neutrinos is cosmic rays scattering from air molecules as shown in Fig. 4. Pions produced in the air decay as $\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu_\mu})$ with further muon decay as $\mu^\pm \to e^\pm + \nu_e(\bar{\nu_e}) + \bar{\nu_\mu}(\nu_\mu)$, which lead to a flux ratio $\Phi(\nu_\mu + \bar{\nu_\mu}) : \Phi(\nu_e + \bar{\nu_e}) \approx 2:1$. Baselines of atmospheric neutrinos experiments are $\sim 10^4$ km, and neutrino energies are ~ 1 GeV. Atmospheric neutrino experiments are more sensitive to $\Delta m^2_{32} = \Delta m^2_{Atm}$, which is also called atmospheric mass splitting, and also provide measurements of θ_{23}. Such experiments are also potentially capable of measuring CP-violating phase δ, but experiments has been performed so far were not sensitive enough to measure δ.

Accelerators can produce ν_μ or $\bar{\nu_\mu}$ similarly as $\nu_\mu(\bar{\nu_\mu})$ are produced in the atmosphere but accelerators can produce high purity ν_μ or $\bar{\nu_\mu}$ beam by choice. Neutrino energies produced by accelerators are ~ 1 GeV, and the baselines are a few hundred kilometers. Fixed baselines and better understood neutrino beam spectra lead to potentially more precise measurements than atmospheric experiments. Accelerator experiments are measuring all neutrino oscillation parameters but the most important targets are Δm^2_{32}, θ_{23}, θ_{13} and δ. However, similarly to atmospheric experiments, the accelerator experiments performed so far were not sensitive enough to measure δ. Having neutrinos long distance to travel through matter make accelerator experiments potentially sensitive to mass hierarchy. Now it is only known that $m_2 > m_1$ and $|\Delta m_{21}| \ll |\Delta m_{32}|$ but it is not known whether $m_3 > m_2 > m_1$ or $m_2 > m_1 > m_3$.

To summarize, among the neutrino oscillation parameters all three mixing angles and two mass differences have been measured, however the sign of Δm^2_{32} is not known and CP-violating phase δ is also not known. Currently available experimental results are summarized in the Table 2.

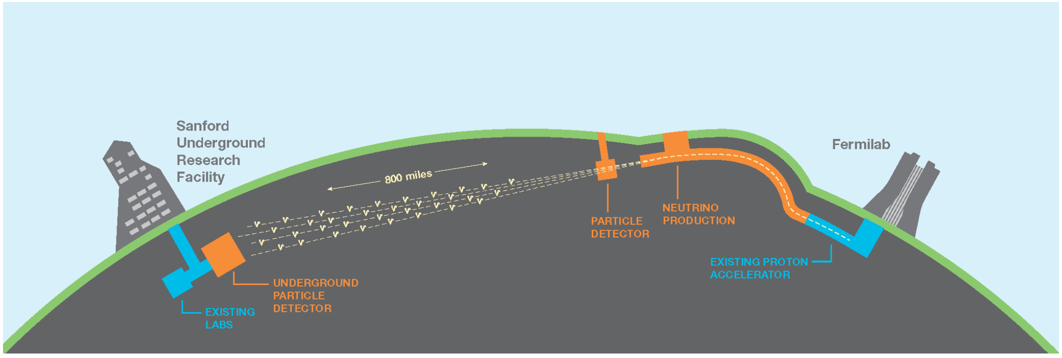
The following questions related to neutrino oscillations remain unknown:

Table 2: Neutrino oscillation parameters measured in other experiments [3].

Parameter	Value and uncertainty	Comment
$sin^2(2\theta_{12})$	0.846 ± 0.021	
$sin^2(2\theta_{23})$	$0.999^{+0.001}_{-0.018}$	if normal mass hierarchy
$sin^2(2\theta_{23})$	$1.000^{+0.000}_{-0.017}$	if inverted mass hierarchy
$sin^2(\theta_{13}), 10^{-2}$	9.3 ± 0.8	first measured in 2012
Δm^2_{21}, $10^{-5} eV^2$	7.53 ± 0.18	$m_2 > m_1$
$\Delta m^2_{32}, 10^{-3} eV^2$	2.44 ± 0.06	if normal mass hierarchy
$\Delta m^2_{32}, 10^{-3} eV^2$	2.52 ± 0.07	if inverted mass hierarchy
m_ν, eV	< 2	

- are the massive neutrinos Dirac or Majorana?
- what is the mass hierarchy ($m_3 > m_2 > m_1$ or $m_2 > m_1 > m_3$)?
- what are the absolute values of the neutrino masses?
- how does the CP-symmetry behave in the lepton sector (what is the value of δ in the neutrino mixing matrix)?
- are the neutrino oscillations an indication of a new fundamental symmetry in particle physics?
- what is the relation between neutrino and quark mixing (if any)?
- can better understanding of neutrino mixing give a hint to matter-antimatter asymmetry in the Universe?
- what is the octant of θ_{23} angle?

Figure 6: LBNF/DUNE overall scheme. The neutrino flux will be produced using existing proton accelerator at Fermilab. Then neutrinos will be registered by the near detector (ND), travel 1300 km to the SURF in South Dakota and be registered by the far detector (FD). Source of figure: [7]



4 LBNF/DUNE Project

While neutrino oscillation physics has significantly developed in recent years, there are still several questions remaining. Previous experiments were not sensitive enough to measure δ phase in the neutrino mixing matrix or to determine mass hierarchy; thus, a new experiment, the LBNF/DUNE, has been proposed to answer remaining issues.

The Long Baseline Neutrino Facility (LBNF) is being internationally designed for the future Deep Underground Neutrino Experiment (DUNE) for the precision measurements of neutrino oscillations parameters and related searches beyond the Standard Model. The general scheme of the facility is shown in Fig. 6. The basic idea of the neutrino oscillation accelerator experiment is to produce a muon neutrino beam, measure neutrino flux a few hundred meters downstream the beam at the near detector (ND), and measure muon neutrino disappearance and/or electron neutrino appearance several hundred kilometers downstream at the far detector (FD). Measurements at two points allow to probe neutrino oscillation predictions. In the case of LBNF/DUNE, beam production system and the ND will be located at Fermilab in Illinois, and the FD will be located 1300 km away at the Sanford Underground Research Facility (SURF) in South Dakota.

The primary focus of the LBNF will be to measure the neutrino oscillation parameters involved in Formula 9, especially

- determine mass hierarchy (sign of Δm_{32});
- measure δ (to determine whether CP-violation is present in lepton sector); and
- determine octant of θ_{23} (now θ_{23} is indistinguishable from 45^0, and it is not clear whether the angle is greater, smaller, or equal to 45^0).

To extract the desired quantities, one would build the $P_{\nu_\mu \to \nu_e}(E_\nu)$ as a function of neutrino energy and perform a fit of the function, allowing the measured quantities as fit parameters in assumptions of two possible mass hierarchies. The number of electron neutrinos registered at the FD and flux of muon neutrinos measured at the ND integrated over a certain amount of time are related as described by Formula 13 [8]:

$$N_{\nu_e}(E_\nu) = \frac{dN_{\nu_\mu}(E_\nu)}{dS} \cdot P_{\nu_\mu \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{\nu_e}, \tag{13}$$

where $N_{\nu_e}(E_\nu)$ is a number of ν_e, $\frac{dN_{\nu_\mu}(E_\nu)}{dS}$ is the flux of ν_μ in the assumption of no oscillations, $P_{\nu_\mu \to \nu_e}(E_\nu)$ is the oscillations probability, $\sigma(E_\nu)$ is the cross section of ν_e interaction with a liquid argon nucleon, ϵ_{ν_e} is the ν_e detection efficiency.

$N_{\nu_e}(E_\nu)$ would be measured at the FD, $\frac{dN_{\nu_\mu}(E_\nu)}{dS}$ would be measured at the ND and then extrapolated to the FD using simulation. Methods used to measure $\sigma(E_\nu)$ and ϵ_{ν_e} in the other neutrino physics experiment (ICARUS) are described in [9]. $P_{\nu_\mu \to \nu_e}(E_\nu)$ is the only unknown term in Formula 13, and it would be fit according to Formula 9.

Key advantages of the LBNF/DUNE experiment compared to other long baseline neutrino experiments (Tab. 4), are a longer baseline which would make the experiment more sensitive to mass hierarchy and CP-violation, higher beam power which would produce more neutrinos and a larger FD mass which would allow to register neutrinos more effectively.

Volume 2 of [5] reports the results of the experiment sensitivity study, calculates expected significances of each of the values to be measured for different values of exposure. Exposure of the experiment is defined as beam power multiplied by the FD mass and by time length of data taking and expressed in $MW \cdot kt \cdot years$ units. For design beam power of 1.07 MW and the FD mass of 40 kt, an exposure of 300 $MW \cdot kt \cdot years$ would correspond to $\sim$7 years of data-taking for reference beam design. For upgraded beam power of 2.4 MW, 300 $MW \cdot kt \cdot years$ would correspond to $\sim$3 years of data taking.

Expected exposures necessary to reach certain physics goals for reference beam are summarized in Tab. 3.

The idea of LBNF/DUNE limitations can be extracted from Fig. 7. The left and the middle plots show expected significances of the MH and the CP determinations as functions of δ/π for certain values of mixing angles. The MH can be determined with almost 5σ significance for any value of δ with an exposure of 300 $MW \cdot kt \cdot years$.

As for the phase δ, it is shown in Fig. 7 (middle) that significance of its measurement drops dramatically as δ approaches 0 or $\pm\pi$ values. The plot shows that for an exposure of 300 $MW \cdot kt \cdot years$, if $|\delta| < 0.2 \cdot \pi$ or $|\pi - \delta| < 0.2 \cdot \pi$, then phase δ can be determined with the significance of less than 3σ. LBNF/DUNE plans on $\sim$ 20 years of data taking which would correspond to exposure of $\sim$ 2000 $MW \cdot kt \cdot years$, but even that may not be enough to determine δ with high enough significance if true value of δ is close enough to 0 or $\pm\pi$.

Fig. 7 (right) shows that if $|45^0 - \theta_{23}| <\sim 2^0$ then the θ_{23} octant can not be determined with better than 3σ significance with the same exposure as gives 3σ significance for 75% of δ values. Fig. 7 shows plots for the NH only but the picture for the IH is similar. More plots, tables and comments about the sensitivity studies are available in [5].

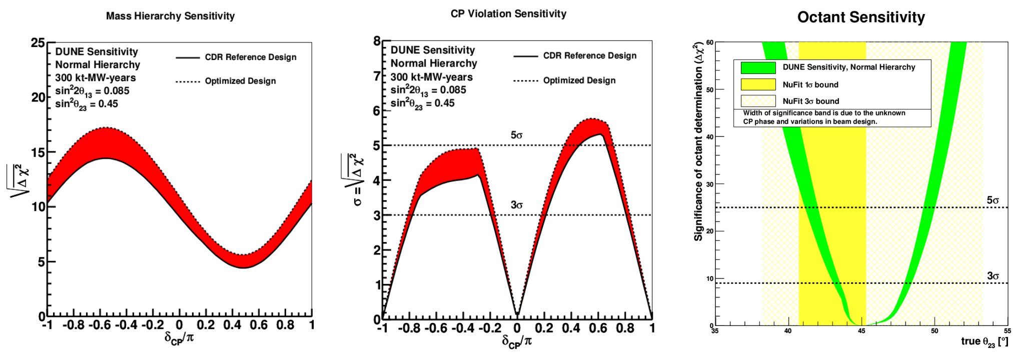
The LBNF neutrino beam will be the highest intensity neutrino beam ever created. The proton accelerator at Fermilab, which was already used in other experiments at Fermilab before, will produce the beam of protons. Then protons will hit a target and create pions and kaons through the strong interactions. Examples of dedicated reactions are: $p + p \to p + n + \pi^+$, $p + p \to p + \Delta^{++} + \pi^-$, $p + n \to p + p + \pi^-$, $p + n \to n + n + \pi^+$, $p + n \to p + \Delta^- + \pi^+$.

After the mesons are created, they go through the focusing system and decay into the decay pipe as $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu_\mu}$, $K^+ \to \mu^+\nu_\mu$, $K^- \to \mu^-\bar{\nu_\mu}$. The branching ratios of charged pions and kaons to decay into $\mu^+\nu_\mu(\mu^-\bar{\nu_\mu})$ are $(> 99.9)\%$ and $(63.55 \pm 0.011)\%$ respectively [3]; therefore, most neutrinos produced into the decay pipe will be muon neutrinos. (While the neutral kaons can also be produced in the target and later decay to pions which could further decay and produce muon neutrinos, the focusing can be applied on charged particles only and therefore neutral particles produced would not contribute to the neutrino beam production unless they decay quickly to charged particles. Neutral pions, π^0s, are very likely to be produced as well but they decay as $\pi^0 \to \gamma\gamma$ and, therefore, can not contribute to the neutrino production.) It is important for the beam production system to operate in both neutrino and antineutrino modes

Table 3: The exposure needed to perform measurements with certain precision expressed in $MW \cdot kt \cdot years$. Estimates provided in the table assume normal mass hierarchy and best fit values of the known parameters. CPV stands for charge-parity violation.

Physics milestone	Exposure
	$[MW \cdot kt \cdot years]$
1^0 θ_{23} resolution (θ_{23} $=$ 42^0)	70
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280
MH at 5σ (at worst)	400
10^0 δ_{CP} resolution at $\delta_{CP} = 0$	450
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525
CPV at 5σ, 50% of δ_{CP}	810
CPV at 3σ, 75% of δ_{CP}	1320

Figure 7: LBNF/DUNE sensitivities to the mass hierarchy (left), the CP-violating phase (middle), and the θ_{23} octant.



by choice to probe Formula 9 for both cases, and the beam production system of the LBNF will be capable of this.

After being produced in the reactions described above, the neutrinos will be detected in the ND at Fermilab. Then the neutrinos will travel 1300 km through the Earth's crust and will be detected at SURF in South Dakota.

One of the most important beam requirements is high intensity to produce a large enough number of neutrinos to perform intended measurements. Beam power of 1.07 MW is expected in the beginning of the experiment with schedule upgrades to 2.4 MW which is four times larger than the highest beam intensity from other experiments of this kind (Tab. 4). Energies of produced neutrinos must cover the first and the second oscillation nodes which corresponds to energies of 0.5-10 GeV for a baseline of 1300 km (Fig. 5). Corresponding proton energies are 60-120 GeV.

Figure 8: Scheme of LBNF/DUNE neutrino beam production system. Source of figure: [7]

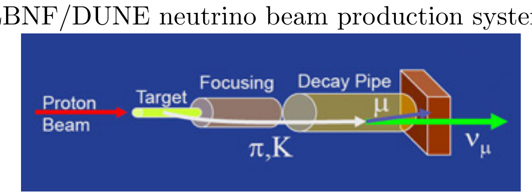
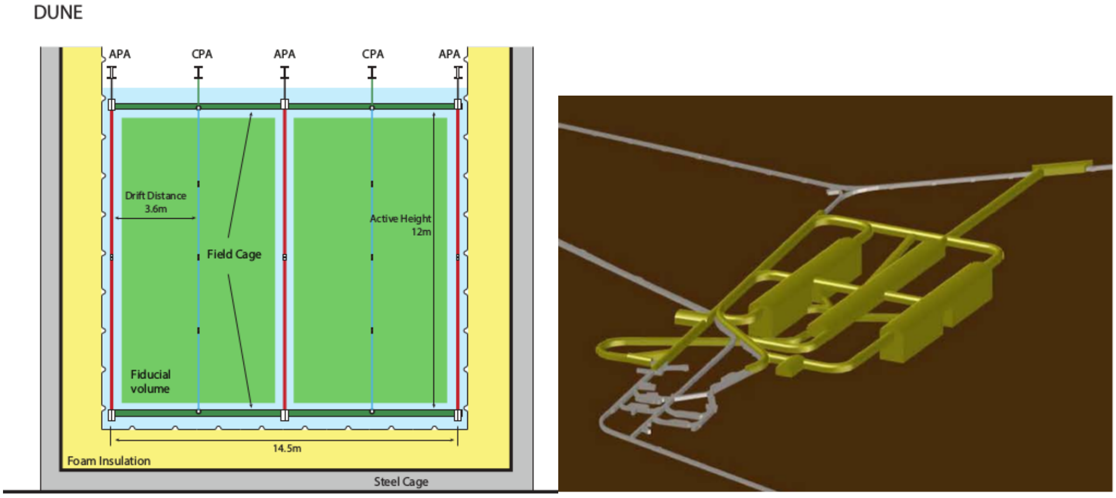


Figure 9: The cross section of the LArTPC for the DUNE FD (left) and the FD caverns (right). Sources of figures: [5]



The main physics goal of the FD would be to measure $N_{\nu_e}(E_\nu)$ from Formula 13 but it would also measure $N_{\nu_\mu}(E_\nu)$ to observe the reduced muon neutrino spectrum. Neutrinos and antineutrinos can produce signal through CC:
$\nu_f + N \to f^- + N' + X$, $\bar{\nu_f} + N \to f^+ + N' + X$,
or through NC:
$\nu_f + N \to \nu_f + N + X$, $\bar{\nu_f} + N \to \bar{\nu_f} + N + X$,
where f is e or μ, N is a proton or a neutron, N' is another baryon, and X is other hadrons produced in the reaction.

In case of CC, the produced charged lepton would be fully reconstructed, and also energy of all the final state particles would be summed up to reconstruct the neutrino energy. In case of NC, neutrino would not be detected, such events would be treated as a background. The FD would be capable to efficiently reconstruct photons, electrons, muons and hadrons.

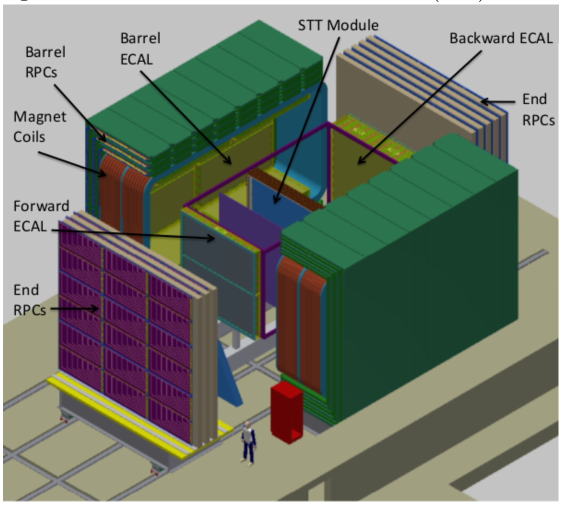
The LBNF/DUNE FD will be located at SURF in South Dakota. There will be four modules, 10,000 tonnes of liquid argon each, placed into four caverns 1500 m underground. Each module will be 15 m wide, 12 m high and 58 m long, along the beam direction. The caverns will be placed as pairs and there will be the fifth cavern between two pairs: the one with the cryogenic equipment, to provide cooling for liquid argon.

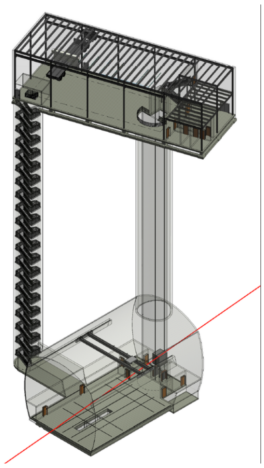
Key advantages of liquid argon as an FD working volume as described in [10] are the ability to act as both a target and a detector, and also to operate as a tracker and a Cherenkov detector at the same time. Liquid argon is denser than water, and therefore such detector would experience more neutrino induced reactions per unit volume than a water detector would.

The liquid argon time projection chamber (LArTPC) is the main working volume of the detector. The chamber is merged into the liquid argon at a temperature of 89 K. In Figure 9, the cathode plane assemblies (CPAs) and the anode plane assemblies (APAs) are shown. The voltages on the APAs and the CPAs are applied in such a way to create a uniform electric field between anode and cathode planes. Charged particle traveling through the electron field ionizes argon atoms. Electrons induced in the ionization process drift to the APAs and produce signal on the readout electronic elements.

The most important physics goal of the ND is to measure the produced muon neutrino flux $\frac{dN_{\nu_\mu}(E_\nu)}{dS}$ as it would go into Formula 13. In the ν_μ beam there is also ν_e contamination

Figure 10: Scheme of the DUNE ND (left) and a related complex (right).





present which would appear as a background at the FD. This background has to be estimated and subtracted. There would also be admixtures of $\bar{\nu_\mu}$ and $\bar{\nu_e}$ in the beam produced. The ND would perform measurement of the overall neutrino and antineutrino flavor composition.

To measure flavor composition, the ND has to be able to reconstruct muons and electrons, and also to be able to distinguish between the opposite sign leptons.

The ND would be located few hundred meters downstream the neutrino beam, and the neutrino beam would be much denser at this point than after traveling 1300 km to the FD, that is why the ND does not have to be as large as the FD. The ND also aims to measure neutrino fluxes with much higher precision than the FD to keep systematic uncertainty of the measurements at the FD smaller than the expected statistical error for data collected during the whole expected time of operation.

Because of different physics goals, the scheme of the ND (shown at the Fig. 10) is also very different from the one of the FD. The detector will consist of the central Straw-Tube Tracker (STT) modules, electromagnetic calorimeter (ECAL), magnet coils of 0.4T and muon identification system consisting of Resistive Plate Chamber (RPC) modules. The neutrinos would come from the bottom left corner of the picture, to the End RPCs. Different sorts of neutrino targets will be built into the tracker, between the Straw-Tubes. The detector will be placed 60 meters underground.

Table 4 provides the comparisons of the LBNF/DUNE most important parameters with those of the other long baseline neutrino experiments: K2K, NuMI, CNGS and T2K [11]. The beam power of LBNF/DUNE is planned to be 2.4 MW while the other operating experiments have only beam powers of few hundred Watts. The baseline of LBNF/DUNE is planned to be 1300 km while the baselines of the other experiments vary from 250 km to 735 km only. The Super-Kamiokande FD has a larger mass than the LBNF/DUNE FD is going to have (50 kt vs 40 kt) but the LBNF/DUNE FD will be filled with liquid argon which is a more favorable substance for neutrino detection than water (which the Super-Kamiokande FD is filled with). The only FD which has liquid argon as working volume is ICARUS but its mass is only 0.76 kt.

LBNF/DUNE is future long baseline neutrino oscillations experiment which will be hosted by two large physics laboratories in USA: Fermilab in Illinois and SURF in South Dakota. LBNF/DUNE's baseline of 1300 km, expected beam power of 2.4 MW, and 40 kt of liquid argon FD makes LBNF/DUNE the most ambitious neutrino oscillations facility ever created. In addition to precision measurements of neutrino mixing parameters such as θ_{12}, θ_{23}, θ_{13}, $|\Delta {m_{12}}^2|$,

Table 4: Comparison of different long baseline neutrino oscillations experiments. Abbreviations and notations used in the table: E_p - proton energy, FGD - Fine-Grained Detector, ChD - Cherenkov Detector, LAr - liquid argon

	KEK (K2K)	NuMI	CNGS	T2K	LBNF/DUNE
location	Japan	Illinois - Minnesota	Switzerland - Italy	Japan	Illinois - South Dakota
accelerator	KEK PS	FNAL	CERN's SPS	J-PARC	FNAL
time of oper.	1999-2004	2005-2012	2006-2012	2010-	future
beam power	5 kW	300-350 kW	300 kW	750 kW	2400 kW
E_p	12 GeV	120 GeV	400 GeV	30 GeV	60-120 GeV
baseline	250 km	735 km	730 km	295 km	1300 km
near detector(s)	(water ChD) (FGD)	MINOS (track. and scint.)	(muon detector)	ND280 INGRID	DUNE (FGD)
ND mass	1 kt (ChD)	0.98 kt			
far detector(s)	SuperK (water ChD)	MINOS track. and scint.	ICARUS (LAr) OPERA (FGD)	SuperK (water ChD)	DUNE (LAr)
FD mass	50 kt	5.4 kt	0.76 kt (ICARUS) 1.25 kt (OPERA)	50 kt	40 kt

$|\Delta m_{32}{}^2|$, it is expected to have enough sensitivity to determine the neutrino mass hierarchy and the CP-violation phase δ which have never been previously determined.

5 Conclusions

Neutrino oscillations were first observed in the 1960s and confirmed in 1998. Neutrinos were believed to be massless for a long time, but the oscillations assume neutrinos to be massive. This phenomenon made the scientific community rethink the theory of weak interactions. While several possible theoretical frameworks to incorporate neutrino masses into the Standard Model have been suggested, it is not clear which hypothesis is true. Precision measurement of neutrino oscillation parameters may bring insight into the understanding of matter-antimatter asymmetry in the Universe and general picture of the generations of the fundamental Standard Model particles.

Neutrino oscillations can be described with four parameters of the neutrino mixing matrix (three angles θ_{12}, θ_{23}, θ_{13} and complex CP-violating phase δ) and the two mass differences (Δm_{21} and Δm_{32}).

Neutrino oscillations can be studied with solar, atmospheric, reactor, or accelerator neutrino experiments. The key idea of any neutrino oscillation experiment is to observe and quantitatively describe disappearance of neutrinos/antineutrinos of certain flavor and/or appearance of neutrinos/antineutrinos of the other flavor. Then probability of neutrinos to oscillate is built and fitted with the assumptions of a certain model, and the neutrino oscillation parameters are extracted.

Significant progress was made in recent years in neutrino oscillation physics with all four types of experiments. Three angles θ_{12}, θ_{23}, θ_{13} have been measured with several degrees precision, absolute values of Δm_{21} and Δm_{32} were measured too, and it is known that $m_2 > m_1$. However, all previous experiments were not sensitive enough to determine the sign of Δm_{32} and the phase δ.

That is why the new LBNF/DUNE experiment was proposed. It will be an accelerator long baseline neutrino oscillations experiment. The highest ever neutrino beam power, the longest baseline and the most effective far detector would make LBNF/DUNE the most ambitious neutrino oscillations experiment in the world and sensitive to effects which were not observed by any other experiment to date. LBNF/DUNE is expected to determine the sign of Δm_{32} with high significance, phase δ in broad range of values, and provide the most precise test of the three-neutrino oscillations theory.

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