Long Baseline Neutrino Facility

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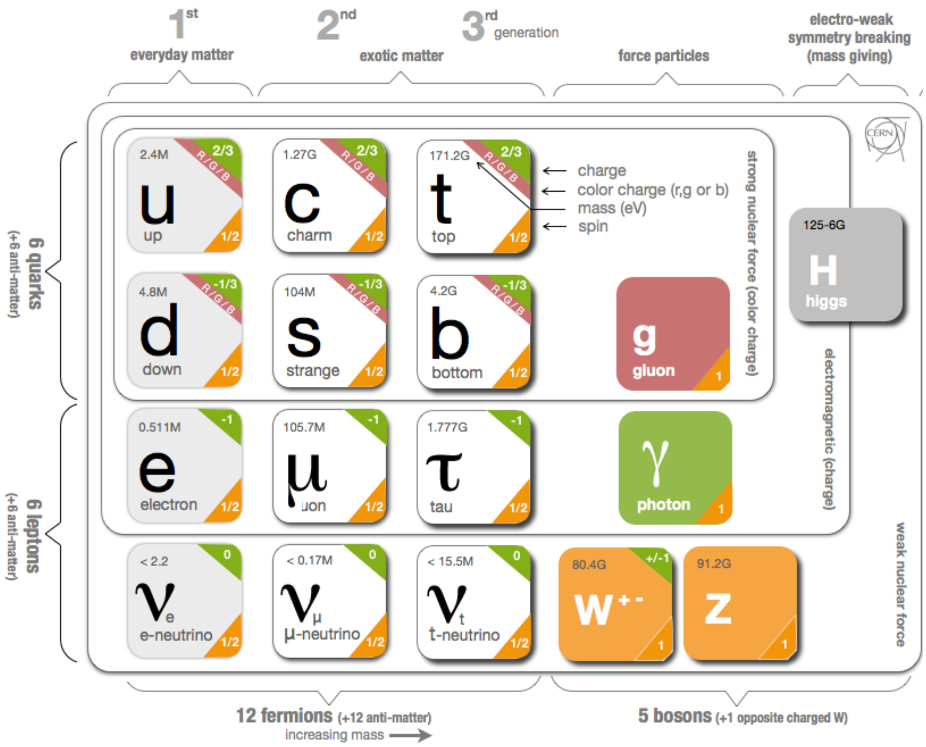
July 12, 2015

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 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 a table like one at fig. 1. It includes three charged leptons, three neutrinos and six quarks and their antiparticles which are split into three generations. In addition, it includes gauge bosons, 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 also posses additional quantum number which is called "color" and can also participate in strong couplings, through exchange of gluons. All those particles and also neutrinos can interact through weak interactions through charged current (CC), by exchanging W-boson, and through neutral current (NC), by exchanging Z-boson. The corresponding Feynman diagrams for the NC and CC are shown at fig. 2

All known substances in the known Universe consist of millions of different species of molecules which are composed by hundreds different species of atoms. Each atom consists of certain number of protons, neutrons and electrons. All protons and neutrons are composed of three quarks (uud for proton and udd for neutron) which are glued together by strong interactions. Therefore, all known substance consists on only three fundamental particles from the Fig. 1: u- and d-quarks and electrons. Despite that neutrinos are not part of substances, a large number of them exist in the nature without any human-built machines. Quoting [3], 11.1: "John Bahcall, who was responsible for most of the calculations of solar neutrino abundances, liked to say that

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

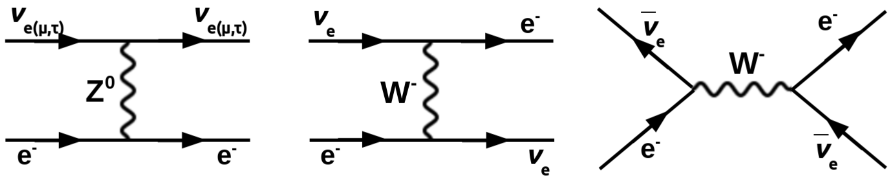
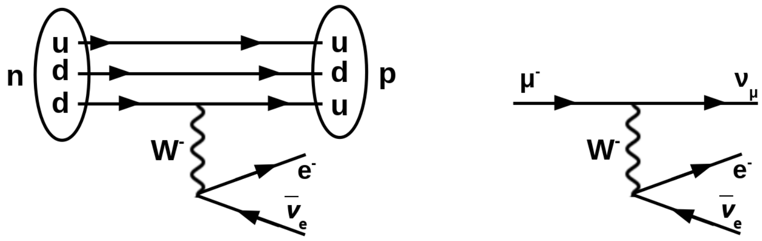


Figure 3: Feynman diagrams of (left) neutron and (right) muon decays. Neutron beta decay is a d-quark transforming into u-quark through the W-boson emission of an electron and an electron antineutrino. A muon decays into an electron, a muon neutrino and an electron antineutrino through a W-boson



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 15 minutes and it decays by $n \to p + e^- + \bar{\nu_e}$ [2]. 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 the neutron decay. When this happens, the electron and electron antineutrino are emitted to conserve the charge and the lepton flavor number. Examples of the neutron beta decay in nature include ${}^{49}{}_{19}K \to {}^{40}{}_{20}Ca$, ${}^{64}{}_{29}Cu \to {}^{64}{}_{30}Zn$, ${}^{3}{}_{1}H \to {}^{3}{}_{2}He$ [3] (the positive beta decay, $p \to n + e^+ + \nu_e$, is forbidden for 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, it's mean lifetime is $2\mu s$, and it decays as $\mu^- \to e^- + \nu_\mu + \bar{\nu_e}$ through the W boson. This process is also common in nature, in cosmic rays: muons are produced in the upper layers of the Earth atmosphere from the interaction of the particles coming from cosmic rays with the atmosphere molecules, for instance, as $p + p \to n + p + \pi^+$ with further pion decay $\pi^+ \to \mu^+ + \nu_\mu$ and then some number of muons decay $\mu^+ \to e^+ + \nu_e + \bar{\nu_\mu}$ while traveling through the atmosphere to the ground. The scheme of the shower in the Earth atmosphere induced by the primary incident proton is shown on fig. 4.

There are three flavors of neutrinos, one for each generation: electron neutrino, muon neutrino, and 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. The table 1 shows the value of this number for all leptons and anti-leptons.

Lepton flavor numbers are 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.

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 $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$.

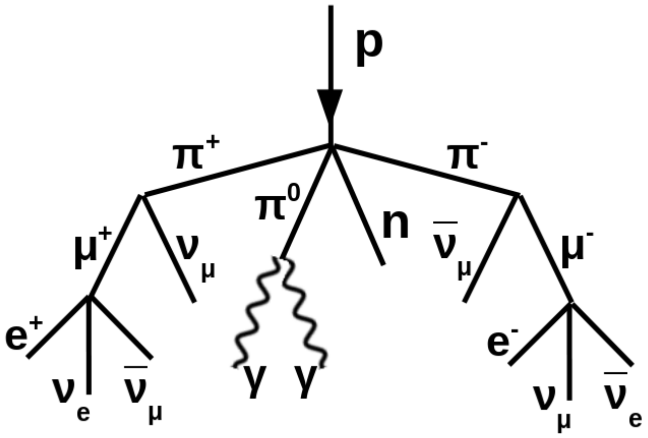


Table 1: Lepton Flavor Number

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

Chapter 2 of this paper reviews the theoretical background of the neutrino oscillations starting from a simplified two-neutrino model in vacuum to a three-neutrino model in 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, milestones achieved by the scientific community in measuring different neutrino oscillation parameters including the most recent experimental results. Chapter 4 explains the need of the 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 simplified model of two-neutrino oscillations in vacuum as it is described in [3], 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:

$$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1 t}{\hbar}},\ \nu_2(t) = \nu_2(0)e^{\frac{-iE_2 t}{\hbar}}$$

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

$$\nu_1(0) = -sin\theta,\ \nu_2(0) = cos\theta,\ \nu_1(t) = -sin\theta e^{\frac{-iE_1 t}{\hbar}},\ \nu_2(t) = cos\theta e^{\frac{-iE_2 t}{\hbar}}$$

Thus, we are getting the system:

$$-sin\theta e^{-\frac{iE_1 t}{\hbar}} = \nu_\mu(t)cos\theta - \nu_e(t)sin\theta,$$
$$cos\theta e^{-\frac{iE_2 t}{\hbar}} = \nu_\mu(t)sin\theta + \nu_e(t)cos\theta$$

By solving this system for ν_e and ν_μ, one would get:

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

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

According to Formulas 1-2, for freely traveling neutrinos, if ν_e was emitted, at any point there is certain probability to register ν_e or ν_μ, and those probabilities change with time periodically, by $[sin(At)]^2$ law. That's 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:

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

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

Therefore, for neutrino oscillations to present in the two-neutrino system, it is necessary that

- neutrino mixing presents ($\theta \neq 0$)
- at least one of two neutrinos is massive, and $m_2 \neq m_1$

Neutrinos were believed to be massless for a long time, and the simplified weak interactions theory normally taught in particle physics classes introduces Lagrangian with massless neutrinos [3]. 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 straightforward mechanisms of giving neutrinos masses 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 ($\nu = \bar{\nu}$) [2], [9]. If the neutrinos are Dirac, both left-handed and right-handed neutrinos must present in the Standard Model Lagrangian, but the right-handed neutrinos term would be significantly suppressed. Only left-handed neutrinos have been experimentally observed to date which is consistent with assumption that right-handed neutrinos present but are much less likely to participate in weak interactions 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.

Remaining part of this chapter considers three-neutrino mixing matrix and $P_{\nu_\mu \to \nu_e}$ is presence of three neutrinos only for Dirac neutrinos case.

Three-neutrino case is described in [9] and [8]. For three-neutrino case, the oscillations are determined by complex unitary matrix which is called Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

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

Arbitrary 3x3 unitary matrix can be parametrized by 9 parameters, but 5 of them can be absorbed as Dirac phases which don't change 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 define $c_{ab} = cos\theta_{ab}$, $s_{ab} = sin\theta_{ab}$, the U_{PMNS} matrix can be split into three multipliers, each would be responsible for mixing of one pair of neutrino flavors:

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

Probability $P_{\nu_\mu \to \nu_e}$ in three-neutrino model in vacuum is given by Formula 5 ([9]):

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

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

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

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

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

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 masses differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$. The mixing angles θ_{12}, θ_{23}, θ_{13} and differences of squared masses $|\Delta m_{12}^2|$ and $|\Delta m_{32}^2|$ are measured and give U_{PMNS} matrix 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 of the important questions in modern particle physics is why the quark mixing angles are so much smaller than neutrino mixing angles and the other important question is whether there is any relationship between quark and neutrino mixing matrices.

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

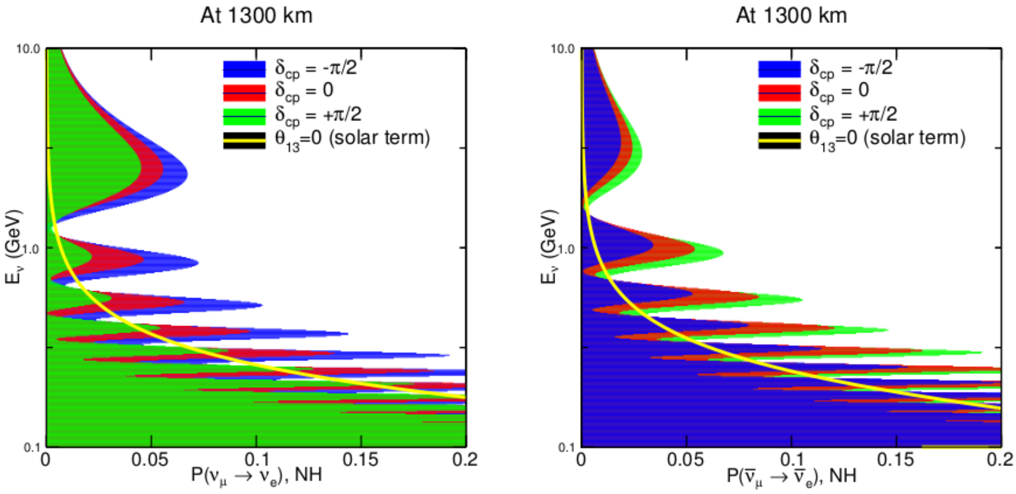
Wave functions of particles and antiparticles are complex-conjugated to each other, and presence of the non-zero complex phase δ in the mixing matrix would mean different behavior for $\nu_\mu \to \nu_e$ and $\bar{\nu_\mu} \to \bar{\nu_e}$ systems. $\delta \neq 0$ would cause charge-spacial parity (CP) violation. Because $|U_{PMNS}|$ mixing matrix involves CP-violating phase, the studies of neutrino oscillations could provide better insight 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 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 quark sector has been observed experimentally, and it can also present in in lepton sector due to δ phase in neutrino mixing matrix. But neutrino oscillations experiments performed before were not sensitive enough to measure δ.

Precision measurements of the parameters of $|U_{PMNS}|$ matrix and comparing it to $|V_{CKM}|$ matrix may bring insight whether there is any relation between quark and neutrino mixing. One especially interesting parameter of $|U_{PMNS}|$ matrix is θ_{32} which is indistinguishable from 45^0 according to currently available experimental results ($sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$ [2]). If $\theta_{32} = 45^0$ exactly, it might be indication of new, unknown symmetry.

Mass differences were measured in other neutrino oscillation experiments, but Δm_{12}^2 and Δm_{32}^2 present in Formula 5 evenly and therefore experiments of neutrino oscillations in vacuum are not sensitive to the signs of these expressions. Ordering of neutrino masses is called mass hierarchy. Determining mass hierarchy can bring 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 mass hierarchy 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 [9]:

Figure 5: $P_{\nu_\mu \to \nu_e}$ for baseline of L=1300 km



$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy. Left - neutrinos, right - antineutrinos. Source of figure: [8].

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

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

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

$$P_3 = cos^2\theta_{23} sin^2 2\theta_{12} \frac{sin^2(aL)}{(aL)^2} \Delta_{21}^2 \tag{12}$$

where $a = G_F N_e / \sqrt{(}2)$, G_F is Fermi constant, and N_e is number density of electrons in the Earth.

For $P(\bar{\nu_\mu} \to \bar{\nu_e})$ one would need to change $\delta \to -\delta$ (because of neutrino-antineutrino asymmetry for CP-violation phase) and $a \to -a$ (because only electrons present in the Earth, not positrons). $a \to -a$ effect introduces sensitivity to mass hierarchy, and increases with L. It was determined that $m_2 > m_1$ however sign of Δm_{32}^2 is unknown. If the masses order as $m_3 > m_2 > m_1$, it's called normal neutrino mass hierarchy (NH), if the masses order as $m_2 > m_1 > m_3$ it is called inverted neutrino mass hierarchy (IH).

The Fig. 5 shows $P_{\nu_\mu \to \nu_e}$ for 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 energies of neutrino/antineutrino. Changes due to different δs are opposite for neutrinos and antineutrinos.

3 Neutrino Oscillations. History and Status

3.1 First Discovery and Confirmation

History of the neutrino oscillations discovery is described in [3], chapter 11. The first evidence of the neutrino oscillations had place in the Homestake experiment in 1968 with solar neutrinos which registered number of neutrinos three times smaller then theoretically predicted. The phenomenon was called "solar neutrino problem". This experiment used Chlorino radiochemical detector. Neutrino interacted with chlorine-37 atom and converted it to argon-37 through the reaction $\nu_e +^{37} Cl \rightarrow^{37} Ar + e$ or, at more fundamental level, $\nu_e + n \rightarrow p + e$. Then argon atoms were separated and counted. The detector was sensitive to electron neutrinos only. Soon after Bruno Pontecorvo proposed the explanation to the solar neutrino problem that neutrino can change it's flavor on it's way from the Sun to the detector. The theory was confirmed by Super-Kamiokande and Sudbury Neutrino Observatory (SNO) collaborations. This experiment used water detector and could register any sort of neutrino through the $e+\nu \rightarrow e+\nu$ scattering. But the NC scattering can not distinguish between different neutrino flavors and also electron neutrinos could interact through CC which made detection efficiency of electron neutrinos 6.5 times higher than other flavors (the left Feynmann diagram at fig. 2 is possible for any neutrino flavor but the middle and right diagrams - only for electron neutrino). Thus, the super -Kamiokande were able to register any neutrino but couldn't 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 were able to measure separately electron and total neutrino flux, confirmed that some of neutrinos coming from the Sun are registered as ν_μ and 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 could get:
$N_{SNO} = 0.35 \cdot N_{th}$
$N_{SK}^{CORR1} = 0.45 \cdot N_{th} = 0.35 \cdot N_{th} + 0.1 \cdot N_{th}$
$N_{SK}^{CORR1} = \frac{N_{SK}^{REG}}{\epsilon^e} = 0.45 \cdot N_{th}$
$N_{SK}^{CORR2} = \alpha \cdot \frac{N_{SK}^{REG}}{\epsilon^e} + (1-\alpha) \cdot \frac{N_{SK}^{REG}}{\epsilon^{\mu/\tau}} = \alpha \cdot \frac{N_{SK}^{REG}}{\epsilon^e} + (1-\alpha) \cdot \frac{N_{SK}^{REG}}{\epsilon^e/6.5}$
$\alpha = 0.35/0.45$
$N_{SK}^{CORR2} = 0.35 \cdot N_{th} + 0.65 \cdot N_{th} = N_{th}$

After that, the neutrino oscillations theory is considered to be confirmed and the solar neutrino problem - resolved.

3.2 First measurements of the neutrino oscillation parameters

angles, mass differences, delta m12, theta13, why delta m31 was not measured and why deltaCP was not measured; read PDG chapter probably

3.3 Recent Experimental Results

The neutrino oscillation parameters measured in other experiments are summarized in the table 2 as quoted in the PDG [2] (section Particle Listings → Leptons → Neutrino Mixing):

According to Particle Data Group Review [2] the following questions will be the main priority to answer by current and future neutrino experiments:

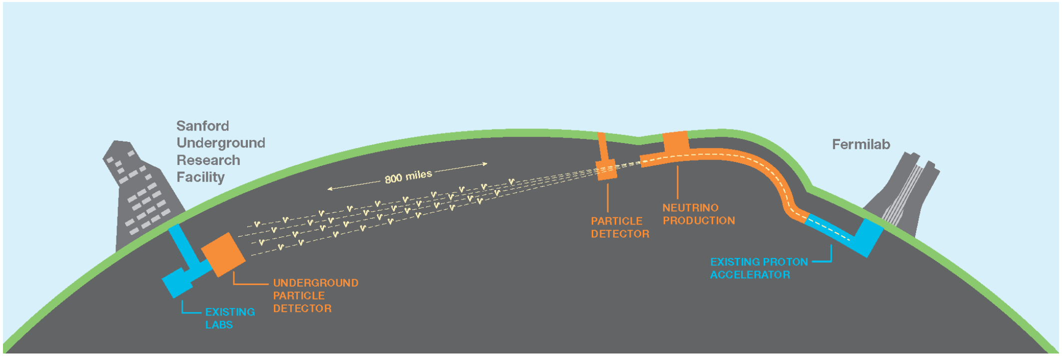
Table 2: Neutrino oscillation parameters measured in other experiments

Parameter	Value and uncerntainty	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	only 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

- whether the massive neutrinos are Dirac or Majorana (Dirac means neutrinos and antineutrinos are dirrefent particles; Majorana means neutrinos are their own's antineutrinos)
- what is the mass hierarchy
- what the absolute values of neutrino masses are
- how does the CP-symmetry behaves in the lepton sector
- are the neutrino oscillations indication of new fundamental symmetry in particle physics
- what is the relation between neutrino and quark mixing if any
- what is the nature of the CP-violation terms in the neutrino mixing matrix
- can better understanding of neutrino mixing give a hint to baryon assymetry in the Universe

In addition, more precise measurement of already measured mixing matrix parameters θ_{12}, θ_{23}, θ_{13}, $|\Delta m_{12}{}^2|$, $|\Delta m_{31}{}^2|$ is also prioritized part of new neutrino experiments physics programs.

Figure 6: Long Baseline Neutrino Facility (LBNF). The neutrino flux will be produced using existing proton accelerator in Fermilab. Then neutrinos will be registered by near detector, travel 1300 km to the Sanford Underground Research Facility in South Dakota and be registed by far detector. Source of figure: [10]



4 LBNF/DUNE Project

The Long Beamline Neutrino Facility (LBNF) is the facility 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 on figure 6.

The overall scheme of the LBNF/DUNE experimental setup is shown at the (fig. 6). The protons from the accelerator will induce the neutrino beam which will be travelling trough the Earth in direction of the far detector in South Dakota. It is common for the long baseline neutrino oscillations experiments to have a near detector (ND) (several hundred meters from the neutrino production) and far detector (FD) (hundreds of kilometers away). Comparing measurements of neutrino flux characteristics at two points allows to extract parameters of neutrino oscillations physics.

4.1 Highlights from LBNF/DUNE Physics Program

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

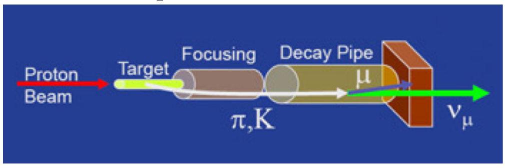
- determine mass hierarchy (sign of Δm_{32})
- measure δ_{CP} (to determine whether CP-violation presents in lepton sector)
- determine octant of θ_{32} (now θ_{32} is indistinguishible from 45^0, and it is not clear whether the angle is greater, smaller, or equal to 45^0)

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

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

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

Figure 7: The neutrino beam production at the LBNF. Source of figure: [10]



efficiency.

$N_{\nu_e}(E_\nu)$ woulb 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. $P_{\nu_\mu \to \nu_e}(E_\nu)$ is the only unknown term in the Formula 13 and it would be fitted according with 9.

Key advantages of the LBNF/DUNE experiment comparing to other long baseline neutrino experiments (Tab. 4), are larger baseline which would make the experiment more sensitive to mass hierarchy and CP-violation as discussed before, higher beam power which would produce more neutrinos and larger far detector mass which would allow to register more neutrinos.

Volume 2 (Physics) of the LBNF CDR draft reports the results of the experiment sensitivity study, calculates expected significances of each of the values to be measured for different values of exposure for reference and optimized beam designs. Exposure of the experiment is defined as beam power multiplied by far detector mass and by time length of data taking and expressed $MW \cdot kt \cdot years$ units. For design beam power of 1.07 MW and far detector mass of 40 kt, exposure of 300 $MW \cdot kt \cdot years$ would correspond to 7 years of data-taking.

Expected exposures necessary to reach certain physics goals for reference beam are summariezed in table 3.

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

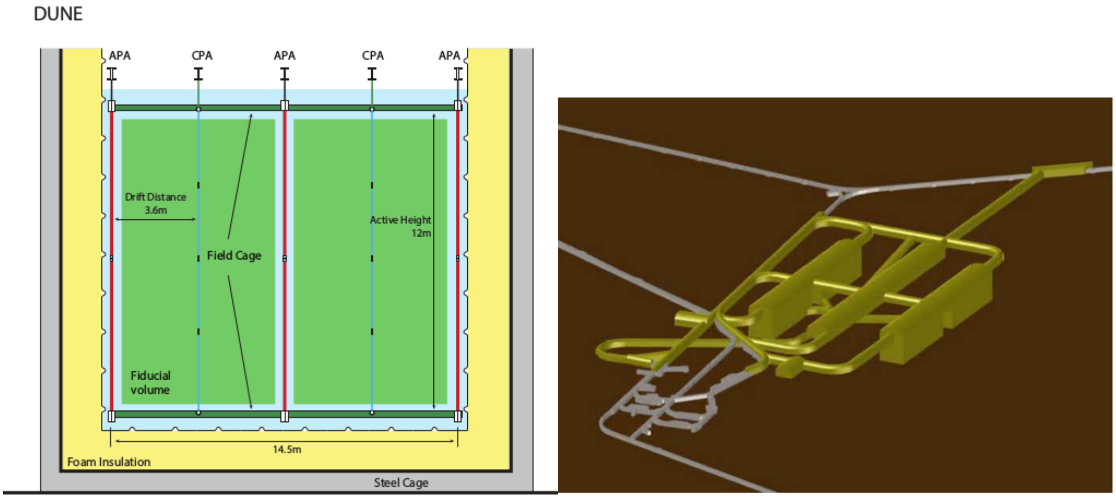
Physics milestone	Exposure
	$[MW \cdot kt \cdot years]$
1^0 θ_{23} resolution ($\theta_{23} = 42^0$)	70
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280
MH at 5σ (at worst)	400
10^0 δ_{CP} resolution at $\delta_{CP} = 0$	450
CPV at 5σ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

4.2 Neutrino Beam

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 through the reactions $p+p \to p+n+\pi^+$, $p+p \to p+\Delta^{++}+\pi^-$, $p+n \to p+p+\pi^-$, $p+n \to n+n+\pi^+$, $p+n \to p+\Delta^- +\pi^+$ and kaons through similar reactions which go strongly through gluon.

After the mesons are created, they go through the focusing system and decay into the decay pipe as $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu_\mu}$, $K^+ \to \mu^+\nu_\mu$, $K^- \to \mu^-\bar{\nu_\mu}$ (fig. **??**). 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 therefore most neutrinos produced into the decay pipe will be muon neutrinos. (While the

Figure 8: The scheme of the cross section of the LArTPC for far detector of the DUNE and far detector caverns. Sources of figures: [?]



neutral kaons can also be produced in the target and later decay in pions which could further decay and produce muon neutrinos, the focusing is being done with the certain configuration of the magnetic field and only can affect charged particles. Neutral pions, π^0s, are very likely to be produced as well but they decay as $\pi^0 \rightarrow \gamma\gamma$ and, therefore, can't contribute to the neutrino production.)
After being produced in the reactions described above, the neutrinos will be detected in the near detector at Fermilab. Then the neutrinos will travel 1300 km through the Earth crust and will be detected at SURF in South Dakota.

One of the most important beam requirements is high intensity to produce large enough number of neutrinos to perform intended measurements. Expected beam power of 1.07 MW is expected in the beginning of the experiment with further update to 2.4 MW which is three times larger than the highest beam intensity from other experiments of this kind. Beam production system must be able to work in both muon neutrinos and muon antineutrinos modes. Energies of produced neutrinos must cover the first and the second oscillation nodes which corresponds to energies of 0.5-5 GeV for baseline of 1300 km. Corresponding proton energies are 60-120 GeV.

4.3 Far Detector

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 the CC:

$\nu_f + N \rightarrow f^- + N' + X$, $\bar{\nu_f} + N \rightarrow f^+ + N' + X$,

or through the NC:

$\nu_f + N \rightarrow \nu_f + N + X$, $\bar{\nu_f} + N \rightarrow \bar{\nu_f} + N + X$

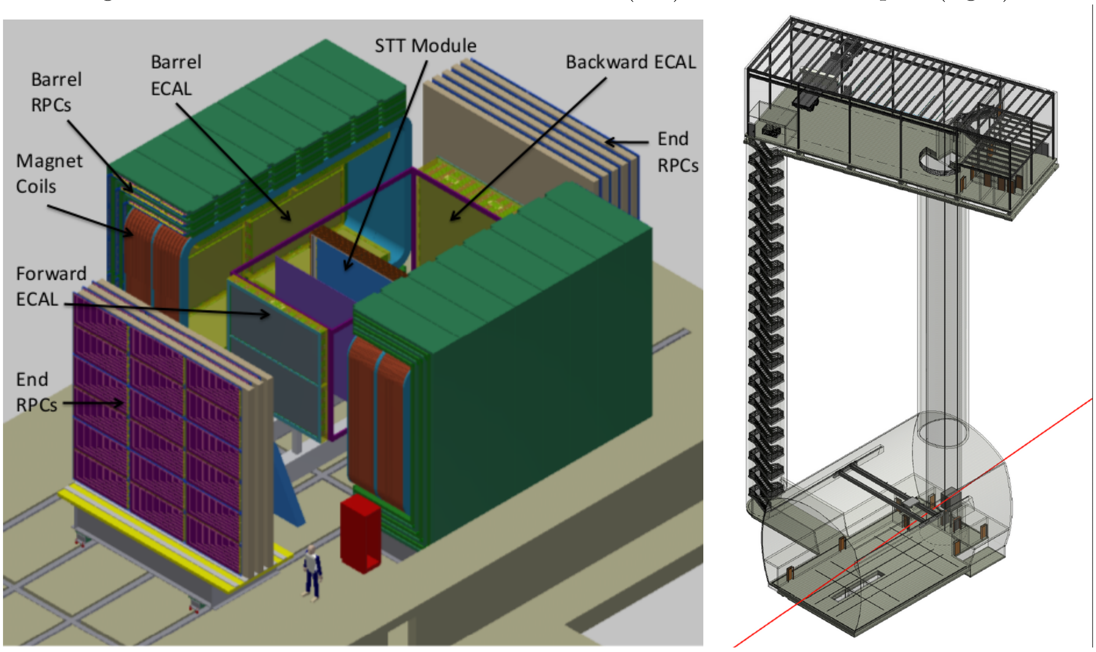
where f is e or μ, N is a proton or a neutron, N' is another baryon, and X is other hadrons produced in the reaction.

In case of CC, the produced charged lepton would be fully reconstracted, and also energy of all the final state particles would be summed up to reconstract the neutrino energy. In case of NC, neutrino wouldn't be detected, such events would be treated as a background.

The detector 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

Figure 9: Scheme of the DUNE Near Detector (left) and related complex (right).



placed as pairs and there will be the fifth cavern between two pairs - the one with the cryogenic equipment, to provide cooling for 89K liquid argon.
Key advantages of liquid argon as a far detector working volume as described in [16] are 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 water detector would.

The liquid argon TPC is the main working volume of the detector. The chamber is merged into the liquid argon at tempetature of 89 K. On the figure 8 the cathod 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 uniform electric field between anode and cathod planes. Charged particle travelling 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.

4.4 Near Detector

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 to Formula 13. In the ν_μ beam there is also ν_e contamination present which would be background to ν_e which would appear as a result of neutrino oscillations at the FD. This background has to be estimated and subtracted. There would be also 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 travelling 1300 km to the FD, that is why the ND doesn't have to be as large as the FD. Also the ND aims on measuring number of neutrinos with much higher precision than the FD to significantly reduce the systematic uncerntainties.

Because of different physics goals, the scheme of the ND (shown at the Fig. 9) is also very different from the one of the FD. The detector will consist of 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. The detector will be placed 60 meters underground.

4.5 LBNF compared to the other long baseline neutrino oscillation experiments

The review article [7] describes beams and detectors of the long baseline neutrino experiments KEK [12], NuMI [13], CNGS [14] and J-PARC [15]. The main parameters, compared to those of the LBNF, are summarized in the table 4. Common in facility setups for all these experiments is that they all include neutrino beam production system incremented to large accelerator facility, tracking near detector allowing precise measurements of the initial beam parameters and large volume far detector. Japanese old experiment K2K which operated in 1999-2004 and it's update T2K use different starting poins (KEK and J-PARC) but the same far detector - Super-Kamiokande, which is 50 kilotonnes water Cherenkov detector. T2K, which already delivered many important results, including the first mearument of θ_{13}, is currently operating and looking forward to perform part of the LBNF physics program too. T2K's baseline is 295 km. The experiment hosted in USA, the NuMI, as well as proposed LBNF, uses neutrino beams produced in Fermilab but it's far detector, MINOS, is located in Minnessota and the experiment's baseline is 735 km. The working volume of the MINOS is magnetized tracker and polysterene scintillator, totalling to 5.4 kilotonnes. The European experiment, the CERN Neutrinos to Gran-Sasso (CNGS), as one can tell from it's name, has it's neutrino beam produced in CERN and the neutrinos measured in Gran-Sasso, Italy. This experiment has two far detectors: fine-grained tracker OPERA and, as well as the DUNE far detector, the liquid argon time-projection chamber ICARUS. But the DUNE has much larger working volume: 4 caverns, 10 kilotonnes each, compared to 760 tonnes ICARUS. As for the beam power, the LBNF is planned to have 2MW while other operating experiments has only beam powers of few hundred Watts. Therefore, among the experiments discussed, the LBNF is going to have the longest baseline (1300 km), the highest beam power and the most sensitive detector (while Super-Kamiokande has larger volume, it's filled with water which is not as favorable for the neutrino detection as liquid argon, as discussed in the subsection "Far Detector"). These characteristics will allow the LBNF to perform more precise measurements than previous and currently existing experiments can do and become sensitive to effects which weren't observed before.

The LBNF is the long baseline neutrino oscillations experiment under development which will be hosted by two large physics laboratories in USA: Fermilab in Illinois and SURF in South Dakota.

The LBNF's baseline of 1300 km, expected beam power of 2 MW, 40 kt of liquid argon far detector makes the LBNF the most ambitious neutrino oscillations facility ever created. In addition to presicion measurements of such neutrino mixing parameters as θ_{12}, θ_{23}, θ_{13}, $|\Delta m_{12}{}^2|$, $|\Delta m_{31}{}^2|$, it's expected to have enough sensitivity to determine the neutrino mass hierarchy and the CP-violation phase δ_{CP} which were never determined before.

Table 4: Comparison of different long baseline neutrino oscillations experiments. Abbreviations and notations used in the table: CNGS - CERN Neutrinos to Gran-Sasso, PS - Proton Synchrotron, J-PARC - Japan Accelerator Resarch Complex, FNAL - Fermilab National Accelerator Laboratory, E_p - proton energy, DUNE - Deep Underground Neutrino Experiment, FGD - Fine-Grained Detector, ChD - Cherenkov Detector, SuperK - Super-Kamiokande, MINOS - Main Injector Neutrino Oscillation Search, OPERA - Oscillation Project with Emulsion-tRacking Apparatus, ICARUS - Imaging Cosmic And Rare Underground Signals, 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	2000 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

5 Conclusions

- Why neutrino oscillations are exciting to study - With what parameters they can be described - How to measure those parameters - What was and what was not measured - Why LBNF/DUNE was proposed and what are the expectation from this experiment

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