Long Baseline Neutrino Facility

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Abstract

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

Contents

Figure 1: Fundamental particles and interactions. Three generations of fundamental particles and interaction mediators. Charged leptons and quarks are subjects to electromagnetic interactions (through photons). Quarks can also interact strongly (through gluons). All leptons and quarks can interact weakly (through $W^{\pm}$ and Z^0 bosons). All these and only these fundamental particles are discovered at the moment. Source of picture: [1]
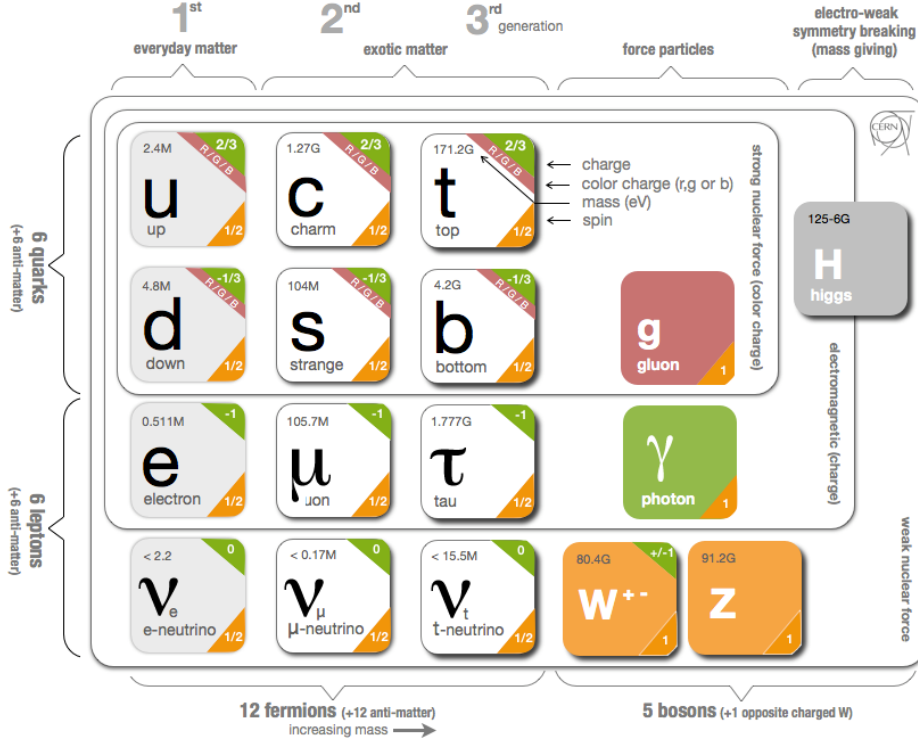
1 Introduction. Neutrinos as Fundamental Standard Model Particles

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 substance in the Universe consists of millions of different molecules which are composed by hundreds different 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 neutrinos are not part of substances, large number of them exists 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 100 billion neutrinos pass through your thumbnail every second; and yet they are so ethereal that you can look forward to only one

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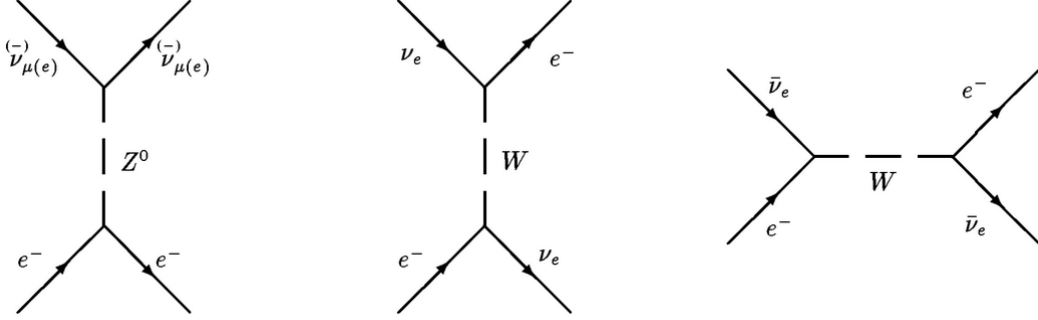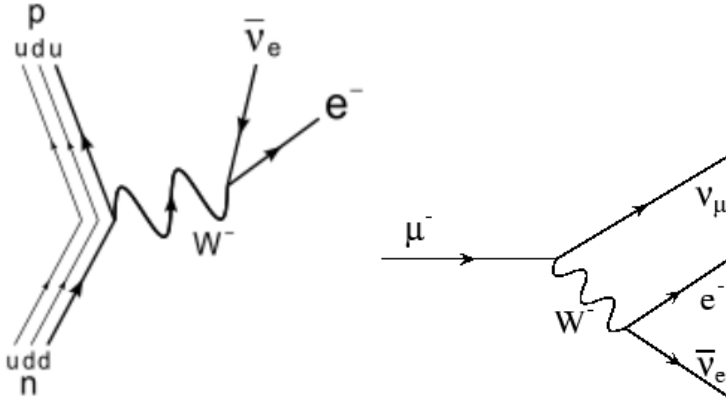

Figure 3: Feynman diagrams of (left) neutron and (right) muon decays. Neutron beta decay (d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino). Muon decay (muon decays to electron, neutrino and antineutrino through W-boson

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 at fig. 3. Mean lifetime of free neutron is 15 minutes and it decays as $n \to p + e^- + \bar{\nu}_e$ [2]. At the level of fundamental particles, neutron consists of two d-quarks and one u-quark and in the beta decay one of the d-quarks transfers to u-quark though the weak interaction mediated by W^- boson. Thus, the proton, which consists of two u-quarks and one d-quark, is being produced. When this happens, the electron and electron antineutrino are emitted to preserve the charge and the lepton flavor number conserved. The 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 law 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 2μs, 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 neutrino, one for each generation: electron neutrino, muon neutrino, τ-neutrino. And 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.

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

Table 1: Lepton Flavor Number
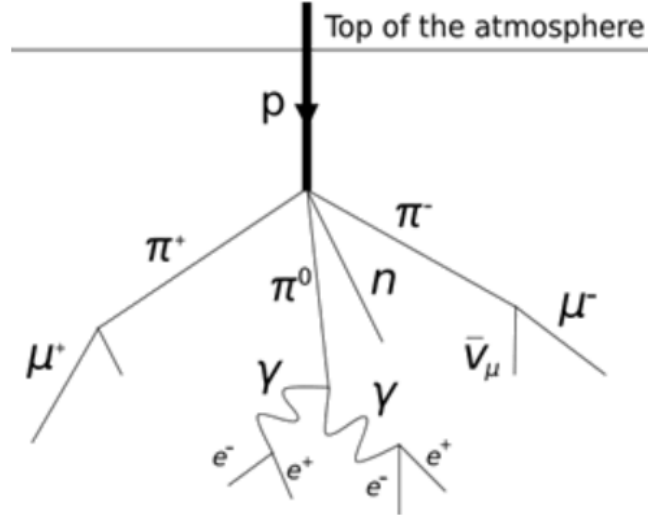
particles	L_e	L_μ	L_τ
e^-, ν_e	+1	0	0
$e^+, \bar{\nu}_e$	-1	0	0
μ^-, ν_μ	0	+1	0
$\mu^+, \bar{\nu}_\mu$	0	-1	0
τ^-, ν_τ	0	0	+1
$\tau^+, \bar{\nu}_\tau$	0	0	-1

The lepton flavor numbers are conserved in almost all particle physics processes and the only violation of this law observed by this time is the neutrino oscillations - the ability of neutrino to change flavor.

Chapter 2 of this paper reviews the theoretical background of the neutrino oscillations starting from simplified two-neutrinos model in vacuum to three-neutrinos model in presence of matter and also discussed possible mechanisms of neutrinos to get masses. Chapter 3 gives historical background to related experimental measurements including the first evidences of neutrino oscillations, milestones achieved by scientific community in measuring different neutrino oscillation parameters and the most recent experimental results. Chapter 4 explains need of the new experiment and gives overview of the proposed LB NF/DUNE experiment in terms of its physics program and experimental setup, it also discusses the advantages of the LBNF/DUNE comparing to the other experiments of this kind. Chapter 5 draws conclusions.

2 Neutrino Oscillations. Theory

2.1 Model of Two-Neutrino Oscillations in Vacuum

Lets consider two neutrinos case as it's described in the chapter 11 of the Griffiths textbook [3]. Suppose there are only two neutrinos ν_e and ν_μ. Then true stationary states of the system would be the orthogonal combinations:

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

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:

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

By solving this sytem for ν_e and ν_μ, one would get

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

Thus, for freely travelling neutrinos, if ν_e was emmitted, at any point there is a certain probability to register ν_e or ν_μ and those probablities 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 $m_{1,2} << E_{1,2}$, the probablities will take forms of

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

2.2 Mechanism of Neutrinos Getting Mass

2.3 Three-Neutrino Oscillation

Three neutrino case is described in the "Long-baseline Neutrino Oscillation Physics" section of the draft Conteptual Design Report (CDR) of the Long Baseline Neutrino Facility (LBNF). For three neutrino case, the oscillations are determined by complex unitary matrix which is called Pontecorvo-Maki-Nakagava-Sakata (PMNS) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The U_{PMNS} matrix depends on three neutrino mixing angles (θ_{12}, θ_{23}, θ_{13}) and CP-violating phase δ_{CP}. If define $c_{ab} = cos\theta_{(ab)}$, $s_{ab} = sin\theta_{(ab)}$, the U_{PMNS} matrix can be splitted into three multipliers, each would be responsible for mixing of one pair of neutrino flavors:

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

The probability amplitudes of neutrino mixing are defined by parameters of the U_{PMNS} but, analogous to simplified two-neutrino case described above, the differences of squares of neutrino masses also contribute to the probability. There are two independent expressionce for squares of masses differences: $\Delta m_{12}^2 = m_1^2 - m_2^2$ and $\Delta m_{32}^2 = m_3^2 - m_2^2$. Mass differences were measured in other neutrino oscillation experiments but the Δm_{12}^2 and Δm_{32}^2 present in the equations evenly and therefore the signs of these expressions were not measured. If the masses order as $m_3 > m_2 > m_1$, it's called normal neutrino mass hierarchy because other fundamental particles orders in a way that later generation particles have higher masses than lower generation particles. If the masses order as $m_1 > m_2 > m_3$ it's called inverted neutrino mass hierarchy. 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 CP-violating phase δ_{CP} 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.

The [9] gives the following expression for $\nu_\mu \to \nu_e$ probability in presence of the Earth matter assuming it has constant density:

$$P(\nu_\mu \to \nu_e) \simeq P_1 + P_2 + P_3 \tag{1}$$

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

$$P_2 = sin2\theta_{23}sin2\theta_{13}sin2\theta_{12}\frac{sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{sin(aL)}{aL}\Delta_{21}cos(\Delta_{31} + \delta_{CP}) \tag{3}$$

$$P_3 = cos^2\theta_{23}sin^2 2\theta_{12}\frac{sin^2(aL)}{(aL)^2}\Delta_{21}^2 \tag{4}$$

where $\Delta_{ij} = \Delta m_{ij}^2 L/4E$, and $a = G_F N_e/sqrt(2)$

For $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ one would need to change $\delta_{CP} \to -\delta_{CP}$ (bacuuse of neutrino-antineutrino assymetry for CP-violationg phase) and $a \to -a$ (because only electrons present in the Earth, not positrons). The effect of $a \to -a$ increases with L which means more sensitivity to mass hierarchy for experiments with larger baseline. The planned baseline of the LBNF is 1300 km and

Figure 5: $P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km
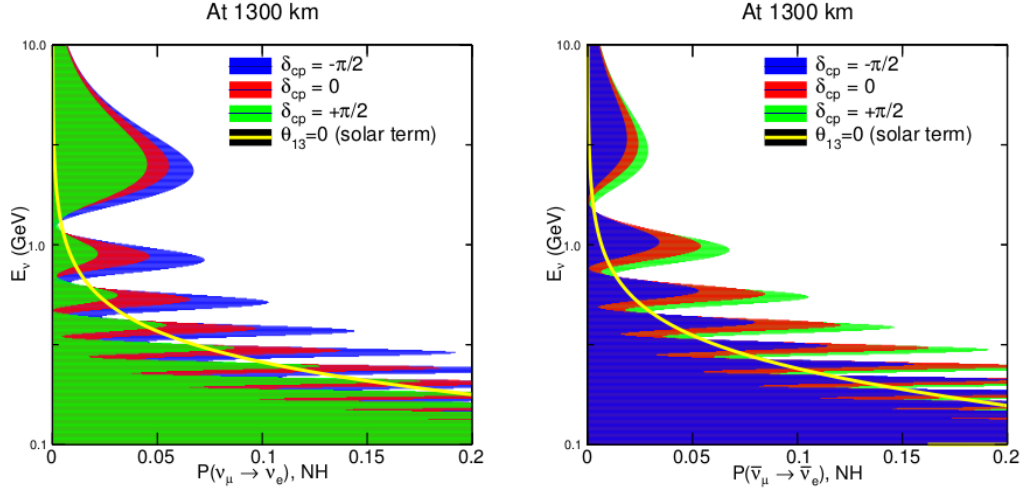
$P(\nu_\mu \to \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy. Left - neutrinos, right - antineutrinos. Figure is taken from the LBNF CDR draft, volume physics[9]

it's expected to be enough to determine the neutrino mass hierarchy and also the CP-violation phase.

The figure 5 shows that magnitude and frequency of oscillations both depend on δ_{CP} and the differences become more significant for higher oscillation nodes which correspond to lower energies of neutrino/antineutrino. Since changes due to different δ_{CP}s are opposite for neutrinos and antineutrinos, it's important for the experiment to operate both.

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 $\rightarrow$ Leptons $\rightarrow$ 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
$\Delta m^2_{21}, 10^{-5}eV^2$	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]
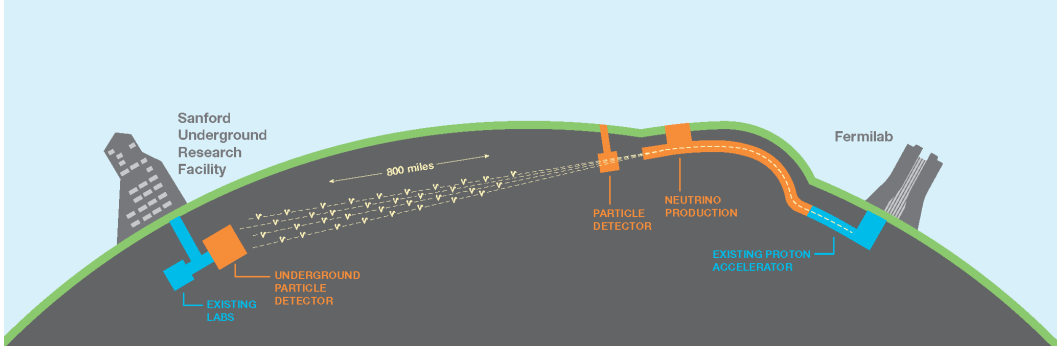
4 LBNF Experimental Setup

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 (several hundred meters from the neutrino production) and far detector (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 1, 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)

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. To extract the desired quantitites, one would build the $P(\nu_\mu \to \nu_e)$ 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.

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 and optimized beams 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, $MW \cdot kt \cdot years$ (reference beam)	Exposure, $MW \cdot kt \cdot years$ (optimized beam)
1^0 θ_{23} resolution ($\theta_{23} = 42^0$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	70
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (at worst)	400	230
10^0 δ_{CP} resolution at $\delta_{CP} = 0$	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ, 50% of δ_{CP}	810	550
CPV at 3σ, 75% of δ_{CP}	1320	850

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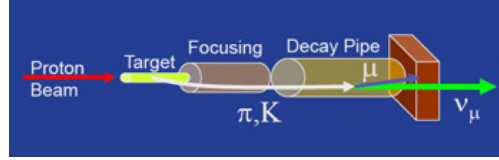
4.2 Neutrino Beam

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 $p + p \rightarrow p + n + \pi^+$, $p + p \rightarrow p + \Delta^{++} + \pi^-$, $p + n \rightarrow p + p + \pi^-$, $p + n \rightarrow n + n + \pi^+$, $p + n \rightarrow p + \Delta^- + \pi^+$ and kaons through similar reactions which go strongly through gluon. In more general words, one quark from the accelerator beam proton scatters on the other quark from the proton or neutron of the target substance as shown at fig. 8. They exchange gluon which produces quark-antiquark pair. At this moment, the system has seven quarks and one antiquark. The antiquark pairs up with one of the quarks participating in the reaction and the remaining six quarks make two baryons in a way to satisfy color charge neutrality in final particles. The charged pions have quark compositions $\pi^+ = u\bar{d}$ and $\pi^- = \bar{u}d$ and can be produced with the reactions which only include first generation quarks. The formulas of charged kaons are $K^+ = u\bar{s}$,

Figure 8: Examples of the Feynmann diagrams of charged pion and kaon productions in proton-proton scattering.
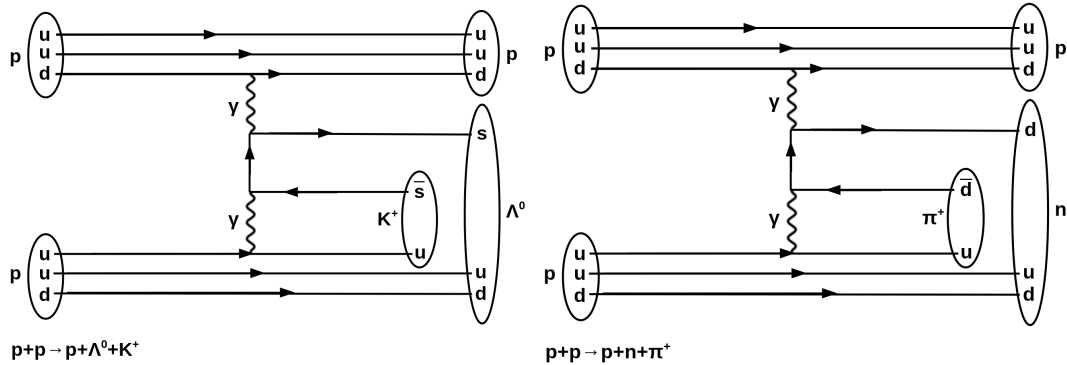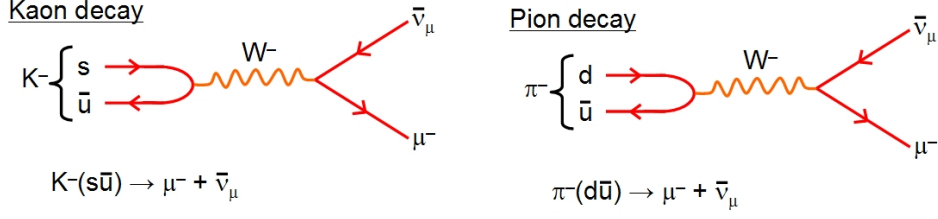
Figure 9: Feynmann diagrams of charged pion and kaon decays to muon and muon antineutrino weakly through W-boson

270 $K^- = \bar{u}s$. Thus, to produce kaons, the gluon has to produce $s\bar{s}$ pair.

271 After the mesons are created, they go through the focusing system and decay into the decay
272 pipe as $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\pi^- \rightarrow \mu^- \bar{\nu_\mu}$, $K^+ \rightarrow \mu^+ \nu_\mu$, $K^- \rightarrow \mu^- \bar{\nu_\mu}$ (fig. 9). The branching ratios of
273 charged pions and kaons to decay into $\mu^+ \nu_\mu (\mu^- \bar{\nu_\mu})$ are $(> 99.9)\%$ and $(63.55 \pm 0.011)\%$ respec-
274 tively therefore most neutrinos produced into the decay pipe will be muon neutrinos. (While the
275 neutral kaons can also be produced in the target and later decay in pions which could further
276 decay and produce muon neutrinos, the focusing is being done with the certain configuration of
277 the magnetic field and only can affect charged particles. Neutral pions, π^0s, are very likely to
278 be produced as well but they decay as $\pi^0 \rightarrow \gamma\gamma$ and, therefore, can't contribute to the neutrino
279 production.)
280 After being produced in the reactions described above, the neutrinos will be detected in the near
281 detector at Fermilab. Then the neutrinos will travel 1300 km through the Earth crust and will
282 be detected at SURF in South Dakota.

283

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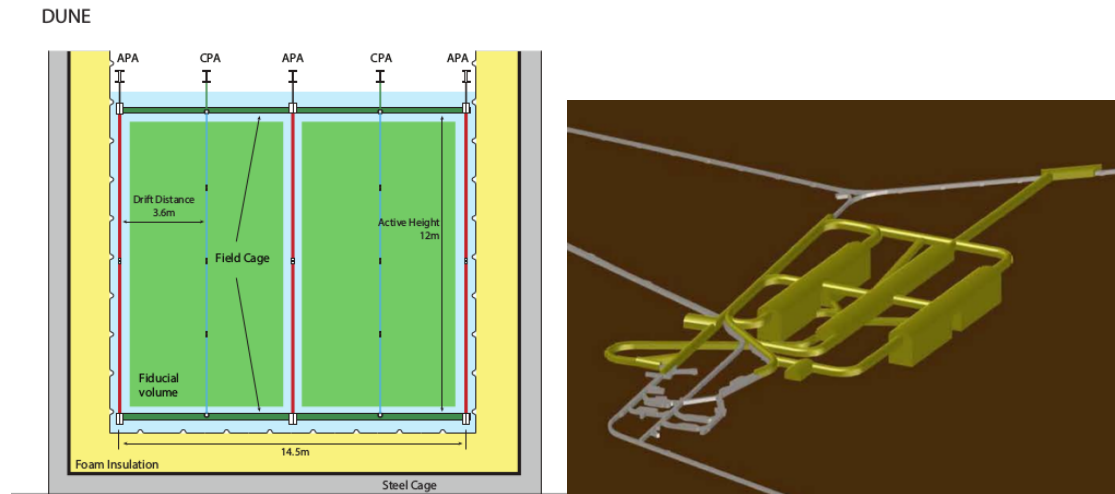
4.3 Far Detector

292 Far detector measures the neutrino flux and energies. After travelling 1300 km, neutrino beam
293 becomes more scattered and therefore far detector needs larger volume to detect neutrinos. It
294 only register electron neutrinos and doesn't aim on as high precision as near detector. That is
295 why far detector is so dramatically different from near detector.
296 LBNF/DUNE far detector will be located at SURF in South Dakota. There will be four modules,
297 10,000 tonnes of liquid argon each, placed into four caverns 1500 m underground. Each module
298 will be 15 m wide, 12 m high and 58 m long, along the beam direction. The caverns will be
299 placed as pairs and there will be the fifth cavern between two pairs - the one with the cryogenic
300 equipment, to provide cooling for 89K liquid argon.
301 Key advantages of liquid argon as a far detector working volume as described in [16] are ability to
302 act as both a target and a detector, and also to operate as a tracker and a Cherenkov detector at
303 the same time. Liquid argon is denser than water, and therefore such detector would experience
304 more neutrino induced reactions per unit volume than water detector would.

305

306 The liquid argon TPC is the main working volume of the detector. The chamber is merged
307 into the liquid argon at tempetature of 89 K. On the figure 10 the cathod plane assemblies
308 (CPAs) and the anode plane assemblies (APAs) are shown. The voltages on the APAs and the
309 CPAs are applied in such a way to create uniform electric field between anode and cathod planes.
310 Charged particle travelling through the electron field ionizes argon atoms. Electrons induced in

Figure 10: The scheme of the cross section of the LArTPC for far detector of the DUNE and far detector caverns. Sources of figures: [8]

the ionization process drift to the APAs and produce signal on the readout electronic elements.
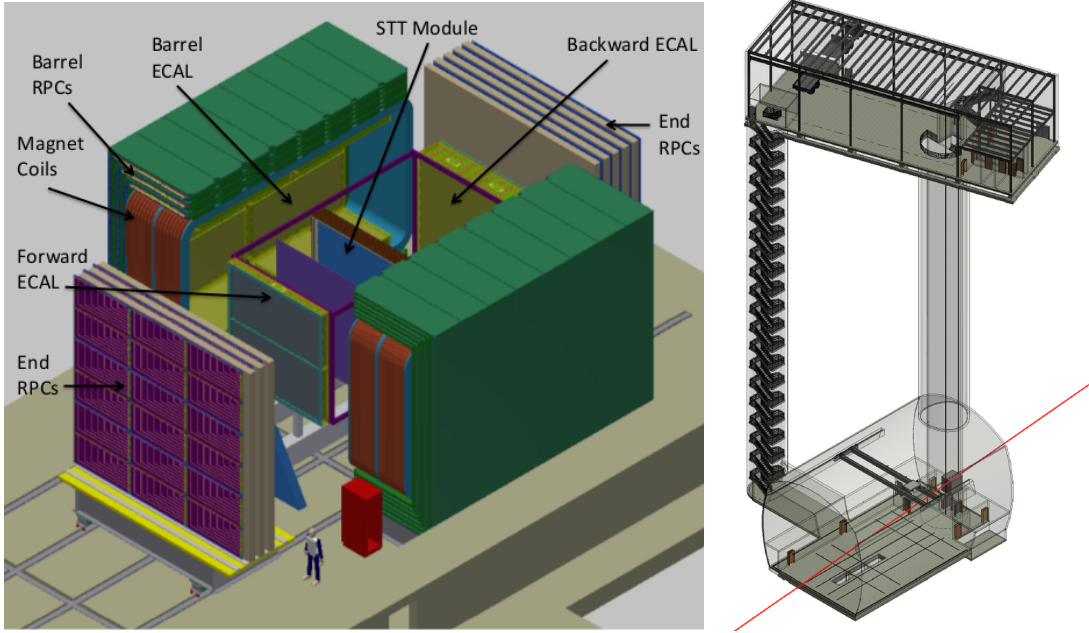
4.4 Near Detector

A near detector is an important part of any long baseline neutrino oscillation experiment. It measures the primary neutrino beam flux as it is produced by the beam production system. Chapter 6 of the draft LBNF CDR [8] lists the following precision measurements to be performed by the Near Detector:

- absolute flux measurement

- relative neutrino and antineutrino flux measurements

- flavor content of the neutrino source

- determination of the E_ν-scale of neutrinos versus antineutrinos

- event-by-event measurements of NC interactions

- measurement of π^0, $\pi^\pm$, $K^\pm$, p, K_S^0 and Λ in the NC and CC

More specifically, the list of the physics measurements related to the neutrino oscillations to be performed by the Near Detector includes:

- fluxes of ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$. To distinguish between flavors, the measurement should rely on charged current interaction (fig. 3, middle and right) and measure the products of these interactions μ^-, μ^+, e^-, and e^+. (While the beam production system has the highest probability to produce muon neutrinos, the production of certain number electron neutrinos is also possible, for example, from charged kaon decays)

- ν_e-$\bar{\nu}_e$ assymetries. For that, it's important not only distinguish between $\mu^\pm$ and $e^\pm$ but also between e^- and e^+.

- the absolute ν_μ and $\bar{\nu}_\mu$ fluxes need to be measured with $\simeq 3\%$ precision in the neutrino energy range 0.5-8 GeV

- cross section of NC versus CC processes as a function of hadronic energy. NC is one of major backrounds which contribute to neutrino oscillation measurement

- yields of π_0 and photons. These particles are the most significant background to ν_e and $\bar{\nu}_e$ contamination

Figure 11: Scheme of the DUNE Near Detector (left) and related complex (right).

338   • fractions of the $\pi^{\pm}$ into the CC and the NC hadronic jets.

339   The scheme of the near detector is shown at the fig. 11. The detector will consist of central
340   Straw-Tube Tracker (STT) modules, electromagnetic calorimeter (ECAL), magnet coils of 0.4T
341   and muon identification system consisting of Resistive Plate Chamber (RPC) modules. The
342   neutrinos would come from the bottom left corner of the picture, to the End RPCs. The detector
343   will be placed 60 meters underground, at least 200 m downstream of the beamline target.

4.5   LBNF compared to the other long baseline neutrino oscillation experiments

346   The review article [7] describes beams and detectors of the long baseline neutrino experiments
347   KEK [12], NuMI [13], CNGS [14] and J-PARC [15]. The main parameters, compared to those of
348   the LBNF, are summarized in the table 4. Common in facility setups for all these experiments
349   is that they all include neutrino beam production system incremented to large accelerator fa-
350   cility, tracking near detector allowing precise measurements of the initial beam parameters and
351   large volume far detector. Japanese old experiment K2K which operated in 1999-2004 and it's
352   update T2K use different starting poins (KEK and J-PARC) but the same far detector - Super-
353   Kamiokande, which is 50 kilotonnes water Cherenkov detector. T2K, which already delivered
354   many important results, including the first mearument of θ_{13}, is currently operating and looking
355   forward to perform part of the LBNF physics program too. T2K's baseline is 295 km. The
356   experiment hosted in USA, the NuMI, as well as proposed LBNF, uses neutrino beams produced
357   in Fermilab but it's far detector, MINOS, is located in Minnessota and the experiment's baseline
358   is 735 km. The working volume of the MINOS is magnetized tracker and polysterene scintilla-
359   tor, totalling to 5.4 kilotonnes. The European experiment, the CERN Neutrinos to Gran-Sasso
360   (CNGS), as one can tell from it's name, has it's neutrino beam produced in CERN and the
361   neutrinos measured in Gran-Sasso, Italy. This experiment has two far detectors: fine-grained
362   tracker OPERA and, as well as the DUNE far detector, the liquid argon time-projection chamber
363   ICARUS. But the DUNE has much larger working volume: 4 caverns, 10 kilotonnes each, com-
364   pared to 760 tonnes ICARUS. As for the beam power, the LBNF is planned to have 2MW while
365   other operating experiments has only beam powers of few hundred Watts. Therefore, among the
366   experiments discussed, the LBNF is going to have the longest baseline (1300 km), the highest
367   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.

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

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 collaboration already include > 750 people and many of them had experience in neutrino physics with other experiments. The first collaboration meeting took place on April 16th-18th of 2015 in Fermilab, ~ 200 scientists came together to discuss their progress and plans towards the LBNF experiment future operation. Completing CDR is one of the short-term goals and the document is well-progressing and it's drafts are partially availabe at the LBNF website. The far detector installation is planned in 2021-2022 in the cavern of the former Homestake mine which in the past hosted another neutrino experiment - the Homestake experiment in 1968 which was the first one to claim the solar neutrino problem. The near detector in Fermilab will require a cavern excavation 60 meters underground and a building construction above it, on surface. The neutrino beam production system will be performed by already existing Fermilab accelerator complex, by team which already has experience in such work: the MINOS experiment which was operating 2005-2012 and is currently under upgrade.

The LBNF's baseline of 1300 km, expected beam power of 2 MW, 40 kt of liquid argon far detector and strong team of people with experience in other experiments of this kind, 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.

However, despite all the advantages of the LBNF and expectations the scientific society has to it, there is still something which this experiment will not be able to measure. For example, the neutrino masses themselves - because neutrino oscillations are only sensitive to differences. Neutrino mass measurement require different kind of experiments - for instance, studiyng high energy cut-off on the electron energy spectrum in beta-decay of tritium. By this time, all the experiments trying to measure it were able only to set upper limits on neutrino masses ([3], 11.4).

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