Long Baseline Neutrino Facility

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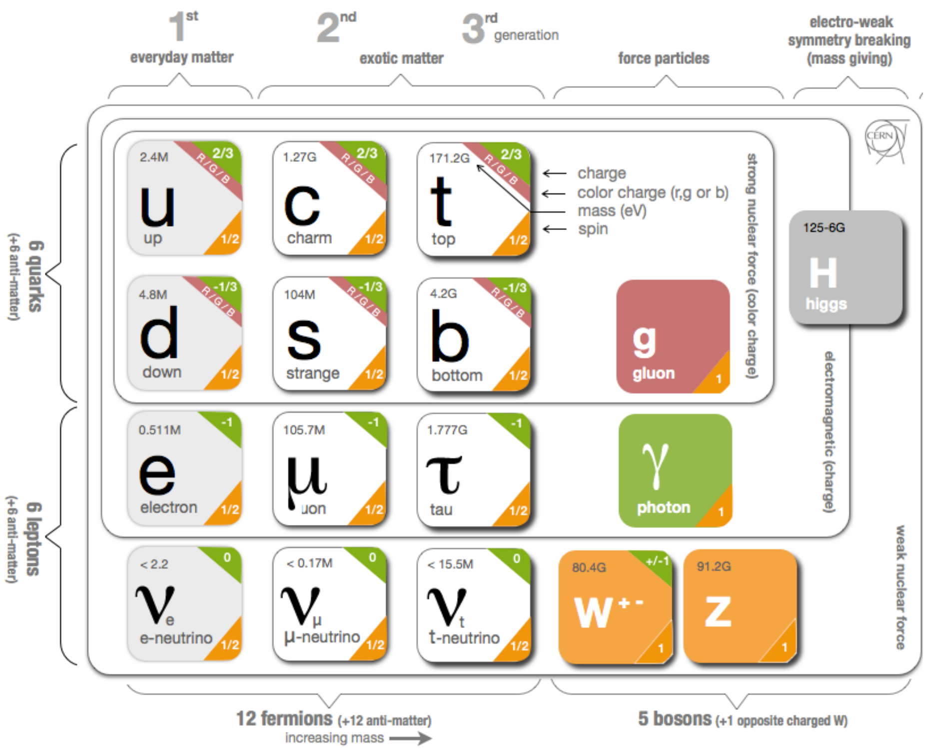
Abstract

The paper reviews the techniques of the Long Baseline Neutrino Facility, which is currently under construction, 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: [9]



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 splitted 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 Feynmann 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 exist in the 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

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

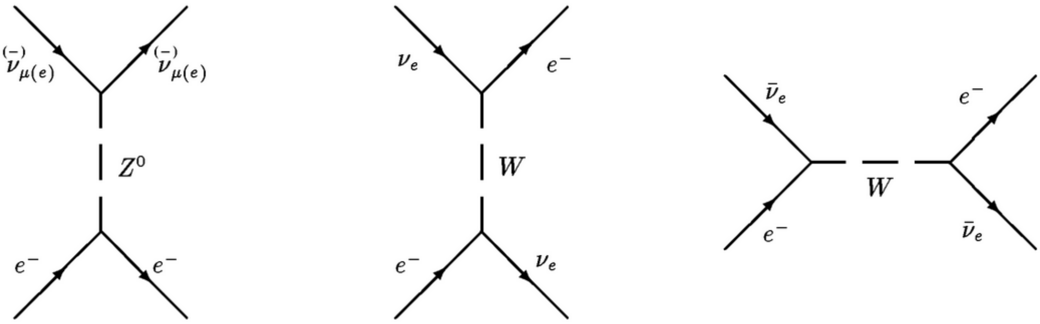
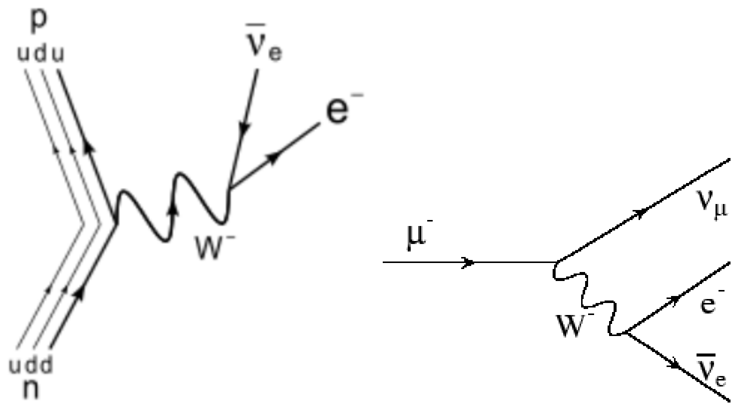


Figure 3: Feynmann diagrams of (left) neutron and (right) muon decays. Neutron beta decay [11](d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino). Muon decay [10](muon decays to electron, neutrino and antineutrino through W-boson



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 Feynmann diagrams of these processes are shown at fig. 3. Mean lifetime of free neutron is 15 minutes and $> 99.9\%$ of those which decay will do it though the beta decay: $n \rightarrow p + e^- + \bar{\nu_e}$ [1]. 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 ${}^{49}{}_{19}K \rightarrow {}^{40}{}_{20}Ca$, ${}^{64}{}_{29}Cu \rightarrow {}^{64}{}_{30}Zn$, ${}^{3}{}_{1}H \rightarrow {}^{3}{}_{2}He$ [2] (the positive beta decay, $p \rightarrow n + e^+ + \nu_e$, is not possible for free proton but it can happen when a proton is part of a nuclei). As for a muon, it's mean lifetime is $2\mu s$ and 99% of muons which decay would do that to electron, muon neutrino and electron antineutrino as $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu_e}$ 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 cosmics with the atmosphere molecules, for instance, as $p + p \rightarrow n + p + \pi^+$ with further pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and then some number of muons decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu_\mu}$ 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 antileptons.

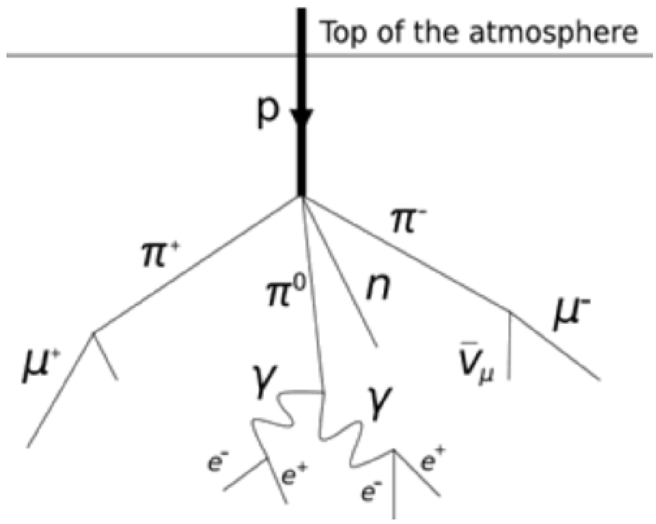


Figure 4: Cosmic shower induced by scattering of the incident cosmics proton of an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \rightarrow \gamma\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$.

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

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.

This paper reviews the theoretical background and the most important experimental measurements related to the neutrino oscillations, related open physics questions which raised over the last several decades, and techniques of the future experiment Long Baseline Neutrino Facility and the anvantages it will have over the other experiments of this kind.

2 Neutrino Oscillations. History and Status

2.1 First Discovery and Confirmation

History of the neutrino oscillations discovery is described in [2], 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:

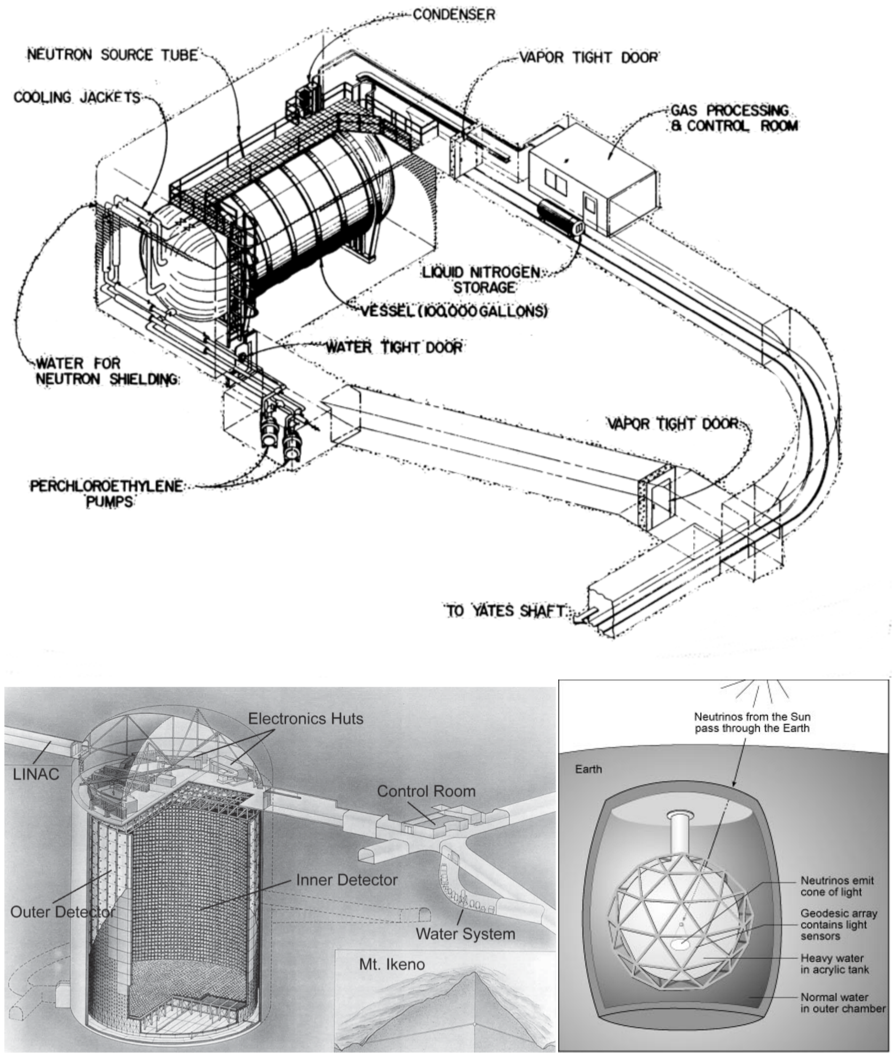
- Homestake experiment (1968): $\nu_e +^{37} Cl \rightarrow^{37} Ar + e$
- Super-Kamiokande experiment (1998): $\nu + e \rightarrow \nu + e$
- Solar neutrino observatory (2002): $\nu_e + d \rightarrow p + p + e$, $\nu + d \rightarrow n + p + \nu$, $\nu + e \rightarrow \nu + e$

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 $45\% = 35\% + 10\%$, $10\% \cdot 6.5 = 65\%$, $35\% + 60\% = 100\%$. After that, the neutrino oscillations theory is considered to be confirmed and the solar neutrino problem - resolved. The schemes of the experiments mentioned are shown at the fig. 5.

2.2 Neutrino Detection Techniques

A particle detection techniques are based on the particle's ability to interact with the detector substance. Probability of neutrino to interact is very small but while most of neutrinos will pass through any detector being unnoticed, the neutrino physics experimentalists concentrate their best efforts on increasing this probability and on detecting those little porion of neutrinos which would interact wih the working substance. Neutrinos can scatter on detector electrons throug weak neutral current (Z-boson). In this interaction, electron would leave the nuclei and would be detected. By measuring electron momentum and energy, it would be possible to receive information about original neutrino erergy and momentum but there would be no information about neutrino flavor. Also, neutrinos can interact through weak charged current ($W^\pm$-bosons) and produce charged lepton ($e^\pm$, $\mu^\pm$ or - if τ-neutrino is energetic enough - $\tau^\pm$). The properties of charged lepton can be measured in the detector and then from momentum and energy conservation laws, the original neutrino properties will be reconstructed. Lepton flavor numbers are always conserved in these reactions and therefore it would be possible to determine the flavor of neutrino too (electron neutrino can only produce electron, muon neutrino can only produce muon and τ-neutrino can only produce τ-lepton). The wikipedia page of Neutrino Detectors list the main detection techniques which make possible to register neutrinos [8]:

Figure 5: Schemes of the Solar neutrino experiments: top: Homestake Experiment , bottom left: Super Kamiokande, bottom right: Sudbury Neutrino Oscillations. Sources of figures: [3], [4], [6].



- Scintillators. Was used in the first experiment which registered antineutrinos - Savannah River nuclear reactor experiment. Water with cadmium chloride solution was used as a target. Antineutrinos from the reactor interacted with protons of the target as $\bar{\nu_e} + p \rightarrow n + e^+$. Then positron annilated with electron $e^+ + e^- \rightarrow \gamma + \gamma$ and the resulting photons are detected by scintillators. The neutron is captured by the cadmium nuclei with radiation of photon. This photon is also detected by the scintillator with delay of several microseconds.
- Radiochemical methods. Chlorino radiochemical detector was used in the Homestake experiment described in the previous subsection. Same idea is used in certain experiments with gallium $\rightarrow$ germanium trasformation. The radiochemical methods are only useful for counting neutrinos but can't measure their kinematic characteristics.
- Cherenkov detectros. A charged particle travelling through the medium with speed $v > c/n$ where c/n - is speed of light in this medium radiate photons which are called Cherenkov radiation. The cherenkov radiation is further detected. Common working substance for this kind of detectors in neutrino physics are ice, water and heavy water.
- Tracking calorimeters. For high energy neutrinos, NC weak interactions cause hadronic shower and CC weak interactions cause electromagnetic shower. The showers produced by charged particle (product of original neutrino interaction) identify track parameters, momentum and energy of the particle.

2.3 Theory of the Neutrino Oscillations

Lets consider two neutrinos case as it's described in the chapter 11 of the Griffiths textbook [2]. 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

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

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:

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

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:

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

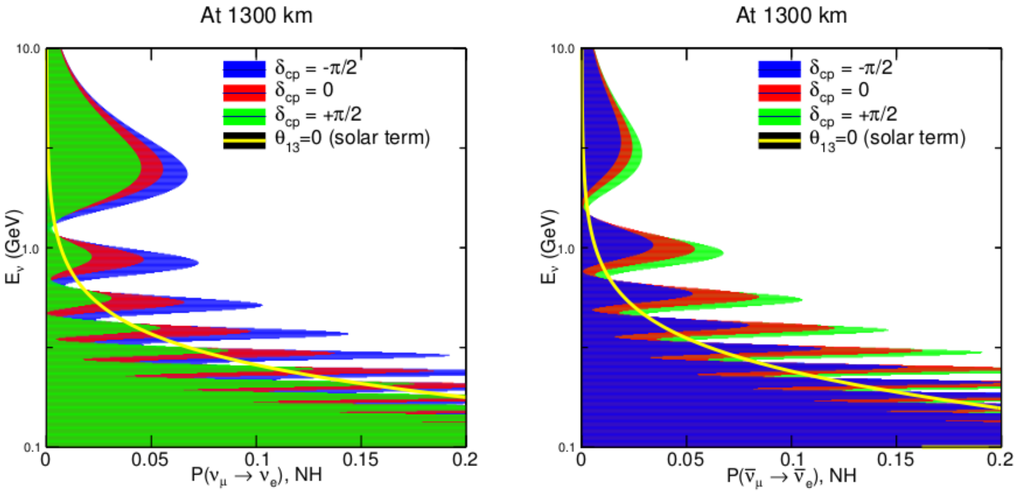
One of the important questions in modern particle physics is why the quark mixing angles are so much smaller than neutrino mixing angles and the other important question is whether there is any relationship between quark and neutrino mixing matrices.

The [13] gives the following expression for $\nu_\mu \to \nu_e$ probability in presence of the Earth matter assuming it has constant density:

$$P(\nu_\mu \to \nu_e) \simeq sin^2\theta_{23} sin^2 2\theta_{13} \tfrac{sin^2(\Delta_{13} - aL)}{(\Delta_{13} - aL)^2} \Delta_{31}^2 +$$
$$+ sin2\theta_{23} sin2\theta_{13} sin2\theta_{12} \tfrac{sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \tfrac{sin(aL)}{aL} \Delta_{21} cos(\Delta_{31} + \delta_{CP}) +$$
$$+ cos^2\theta_{23} sin^2 2\theta_{12} \tfrac{sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

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

Figure 6: $P(\nu_\mu \to \nu_e)$ 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[13]

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

The figure 6 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.

2.4 Recent Experimental Results

The neutrino oscillation parameters measured in other experiments are summarized in the table 2 as quoted in the PDG [1] (section Particle Listings → Leptons → Neutrino Mixing):

Table 2: Neutrino oscillation parameters measured in other experiments

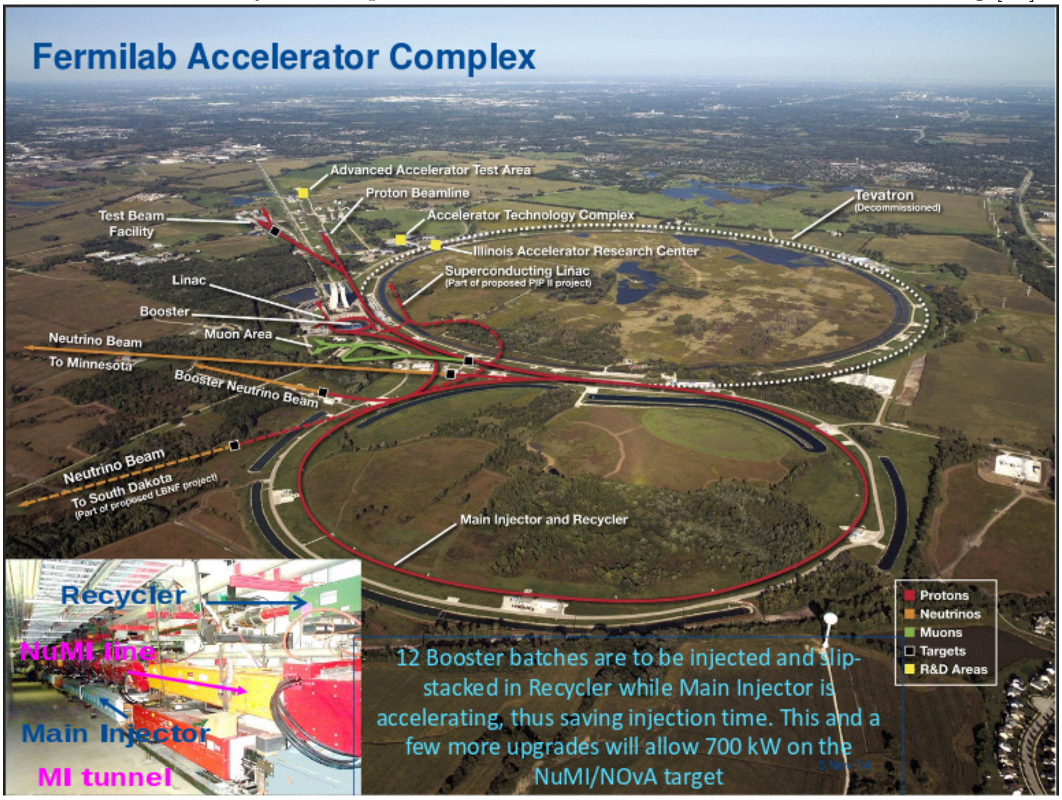
Parameter	Value and uncertainty	Experiment(s)
$sin^2(2\theta_{12})$	0.846 ± 0.021	KamLAND + global solar + SBL +accelerator: 3ν
$sin^2(2\theta_{23})$	$0.999^{+0.001}_{-0.018}$	T2K (if normal mass hierarchy)
$sin^2(2\theta_{23})$	$1.000^{+0.000}_{-0.017}$	T2K (if inverted mass hierarchy)
$sin^2(\theta_{13}), 10^{-2}$	9.3 ± 0.8	DayaBay, Chooz, Yonggwang
Δm^2_{21}, $10^{-5}eV^2$	7.53 ± 0.18	KamLAND + global solar + SBL +accelerator: 3ν
$\Delta m^2_{32}, 10^{-3}eV^2$	2.44 ± 0.06	T2K, MINOS, DAYA(if normal mass hierarchy)
$\Delta m^2_{32}, 10^{-3}eV^2$	2.52 ± 0.07	T2K, MINOS, DAYA (if inverted mass hierarchy)

According to Particle Data Group Review [1] the following questions will be the main priority to answer by current and future neutrino experiments:

- 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 7: The Fermilab Accelerator Complex as it is described in the presentation "The LBNF Beamline and PIP-II" by Vaia Papadimitriou at the fisrt LBNF Collaboration meeting [16]



3 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 8. The first collaboration meeting took place on April 16th-18th of 2015 in Fermilab [16]. There were about 200 participants out of total of 750 members. The statuses and prospectives of the Near Detector, Far Detector, Neutrino beam, software infrastructure and other related technical topics were discussed. Most information written in this section is taken from the presentations of this collaboration meeting, the Concettual Design Report (CDR) drafts [12], [13] and the main pages of the LFNF website [14].

Scheme of the Fermilab accelerator complex is shown at the (fig. 7) and the overall scheme of the Long Baseline Neutrino Facility (LBNF) is shown at the (fig. 8). The protons from the accelerator will induce the neutrino beam which will be travel trough the Earth in direction of the Deep Underground Neutrino Experiment (DUNE) 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.

General requirements for the experiment are listed in [12].

- neutrino beam of high intensity which would be able to produce large amount of neutrinos to be registered at the far site
- the detector to register neutrinos and measure the beamline characteristics at the near site
- the liquid argon time-projection chamber for the far site detector (LArTPC)

Figure 8: 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: [14]

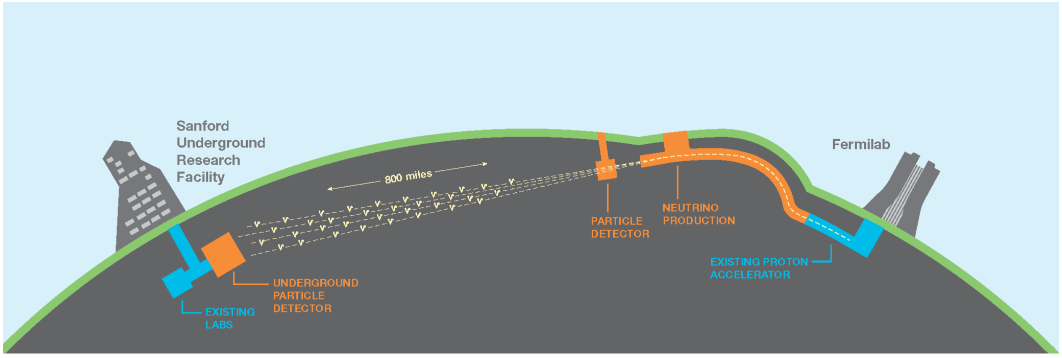
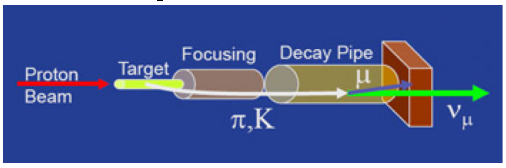


Figure 9: The neutrino beam production at the LBNF. Source of figure: [14]



3.1 Neutrino Beam

The LBNF neutrino beam will be the highest intensity neutrino beam ever created. The proton accelerator in Fermilab which was already used in other experiments in Fermilab before will produce the beam of protons. Then protons will hit a target and create kaons and pions through the same reactions as take place in atmosphere when the cosmic protons hit molecules of air. Pions can be created in the reactions $p+p \to p+n+\pi^+$, $p+p \to p+\Delta^{++}+\pi^-$, $p+n \to p+p+\pi^-$, $p+n \to n+n+\pi^+$, $p+n \to p+\Delta^- +\pi^+$ etc which go electromagnetically though photon. 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. 10. They exchange photon 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. The charged pions have formulas $\pi^+ = u\bar{d}$ and $\pi^- = \bar{u}d$ and can be produced with the reactions which only include first generation quarks. The formulas of charged kaons are $K^+ = u\bar{s}$, $K^- = \bar{u}s$. Thus, to produce kaons, the photon has to produce

Figure 10: Examples of the Feynmann diagrams of charged pion and kaon productions in proton-proton scattering.

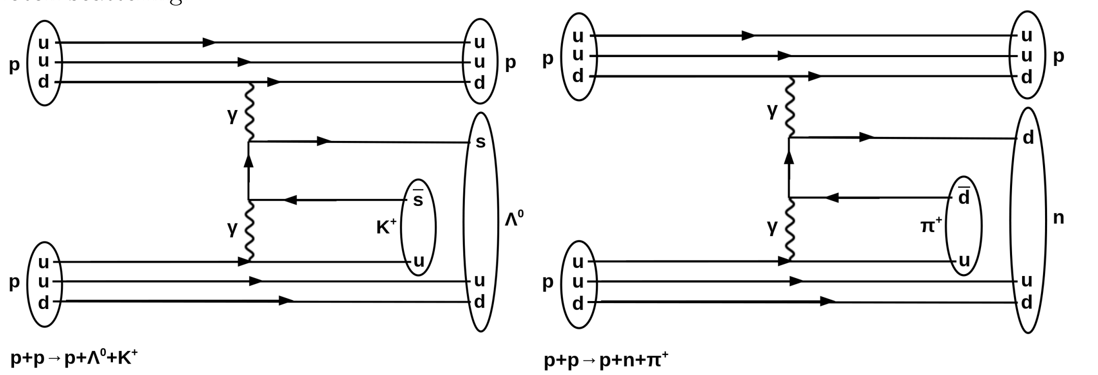
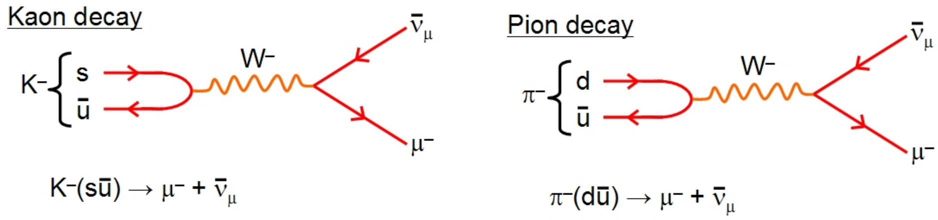


Figure 11: Feynmann diagrams of charged pion and kaon decays to muon and muon antineutrino weakly through W-boson. Figures taken from [15].



$s\bar{s}$ pair.

After the mesons are created, they go through the focusing camera and decay into the decay pipe (the length of the decay pipe is about 200 meters) as $\pi^+ \rightarrow \mu^+\nu_\mu$, $\pi^- \rightarrow \mu^-\bar{\nu_\mu}$, $K^+ \rightarrow \mu^+\nu_\mu$, $K^- \rightarrow \mu^-\bar{\nu_\mu}$ (fig. 11). The branching ratios of charged pions and kaons to decay into $\mu^+\nu_\mu(\mu^-\bar{\nu_\mu})$ are (> 99.9)% and (63.55 ± 0.011)% respectively 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 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 in the Fermilab. Then the neutrinos will travel 1300 km through the Earth crust and will be detected by Sanford Underground Research Facility in South Dakota.

Beam requirements listed in the "Beam Requirements and Beam Optimization talk" during the first LBNF collaboaration meeting include:

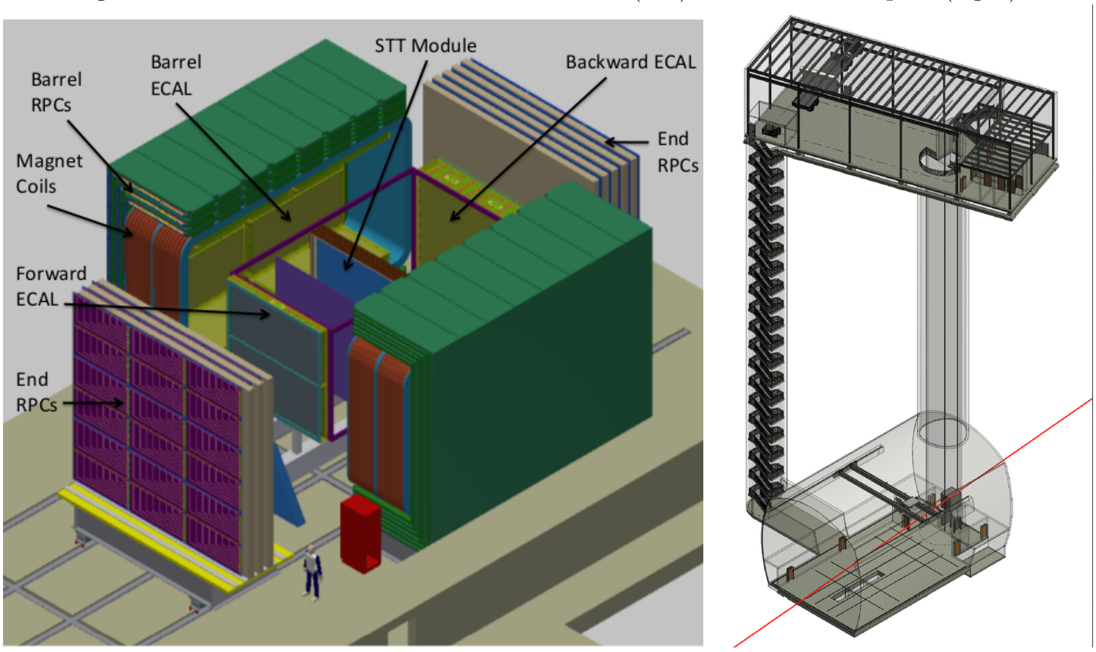
- the beam must have high intensity, be wide-band
- must be able to produce muon neutrinos or antineutrinos by experimenter's choice
- fraction of the opposite sign neutrinos must be small
- the energy range of the first oscillation node (1-5 GeV) must be fully covered
- the second oscillation node, ~ 0.8 GeV must be achievable too
- must work at $>\sim 2$ MW at 60-120 GeV/c
- the option to tune the lower primary proton momenta down to 60 GeV/c must present
- the parameters of the neutrino flux must be stable

3.2 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 [12] 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

Figure 12: Scheme of the DUNE Near Detector (left) and related complex (right).



- 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
- nucleon structure, parton distribution functions and QCD studies
- precision measurements of electroweak physics

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

The scheme of the near detector is shown at the fig. 12. 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.

Quoting the LBNF website [14], "The DUNE near detector will require LBNF to excavate and provision a cavern 200 ft (60 m) below grade on the Fermilab site and to construct a surface building directly above it. An elevator will provide the primary access between the two spaces; the stairway shown is planned for emergency egress. This complex will be constructed a minimum of 690 feet (210 m) downstream of the beamline target."

3.3 Far Detector

The LBNF website [14] provides general description of the DUNE far detector which to be located at Sanford Undergroud Research Facility (SURF) in South Dakota. General view pictures of the facility are shown at fig. 13 and fig. 14. 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 89K liquid argon and to keep agron pure and circulating smoothly during operations. That's how Tia Miceli, postdoctoral reaseacher at New Mexico State University, in her article for the "Fermilab today" [23] explains why liquid argon is excellent working substance for neutrino detectors: "For particle physics, perhaps liquid argon's most important feature is that it acts as both a target and detector for neutrinos < ... > With 40 protons and neutrons, liquid argon is denser than water or oil, so liquid-argon detectors see more neutrino collisions per unit volume than their oil- or water-based predecessors. That means faster measurements and consequently faster discoveries. Another advantage of liquid argon is that, when a neutrino interacts with it and subsequently generates charged particles, it produces two separate kinds of signals; oil- or water-based detectors produce only one. One type of signal, unique to liquid argon, results from its ability to record the charged particles' trajectories. Charged particles are created in the liquid argon after a neutrino flies in and collides with an argon nucleus. The charged debris travels through the argon and easily knocks off electrons from the neighboring atoms along its path. The electronic traces in the liquid argon are pushed by an applied electric field toward an array of wires (similar to a guitar's) on the side of the detector. The wires collect data on the particle trajectories, producing a signal. The second signal type is one shared with oil- and water-based detection: a flash of light. When a charged particle bumps into an argon atom's electron, the electron transitions to a higher energy. As the electron transitions back to its original state, the excess energy is emitted as light. It turns out that argon is also relatively cheap. Companies liquefy air and heat it slowly. Since each of air's components has a unique boiling temperature, they can be separated. The boiled-off argon is moved to a separate chamber where it is again condensed. The commercially available liquid argon that we buy is still not pure enough for our experiments, so once the liquid argon arrives at the lab, we filter out the remaining impurities by a factor of 10,000." [she means for the proposed LBNE experiment which now transitioned to the discussed here LBNF]

The Far Detector consists of

- Liquid Argon Time Projection Chamber (LArTPC)
- Data Aquisitin System (DAQ)
- Cold Electronics
- Photon Detector (PD)

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 15 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. The important requirements to the TPC include:

- be able to perform electron/photon discrimination
- wire sag shouldn't affect the position and energy resolutions

Figure 13: Sanford Underground Research Facility (SURF)

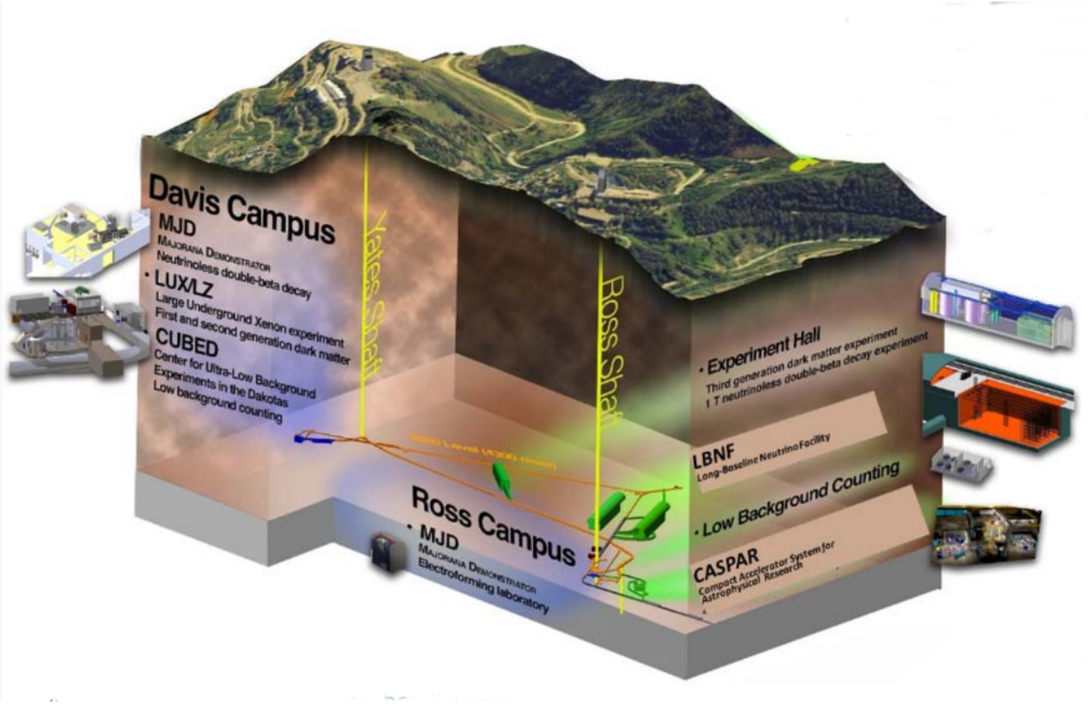
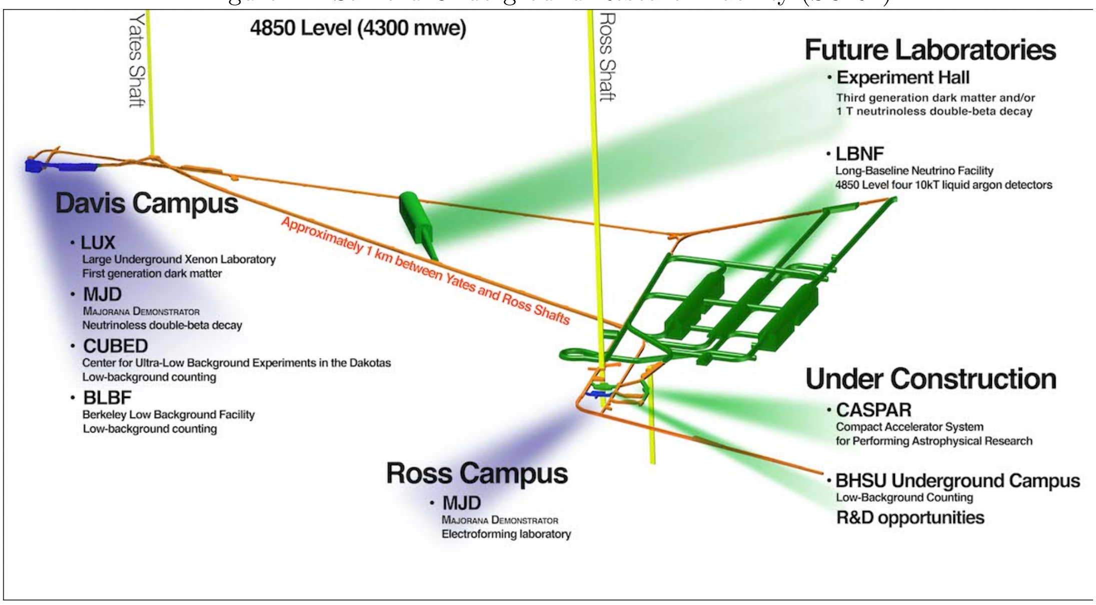


Figure 14: Sanford Underground Research Facility (SURF)



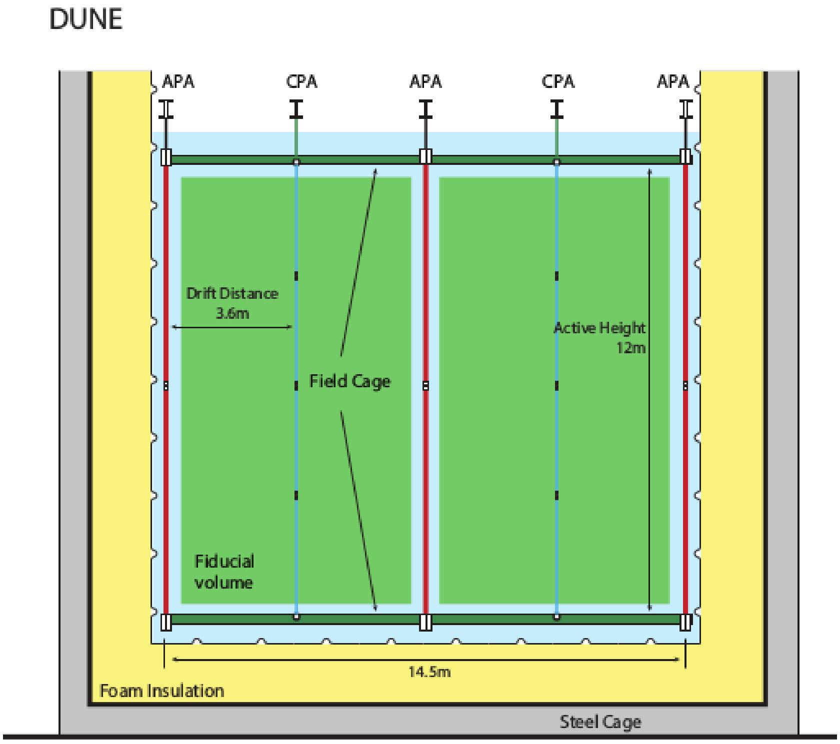


Figure 15: The scheme of the cross section of the LArTPC for far detector of the DUNE. Source of figure: [12]

- discriminate electrons coming from photon conversion from primary electrons
- has good performance in measurements of high-energy and low-energy tracks
- make sure that materials used wouldn't contaminate high purity argon

3.4 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 [19], NuMI [20], CNGS [21] and J-PARC [22]. The main parameters, compared to those of the LBNF, are summarized in the table 3. 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.

Table 3: 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

4 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 ([2], 11.4).

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