Long Beam Neutrino Facility and Neutrino Mixing

Ekaterina Avdeeva

University of Nebraska-Lincoln, USA

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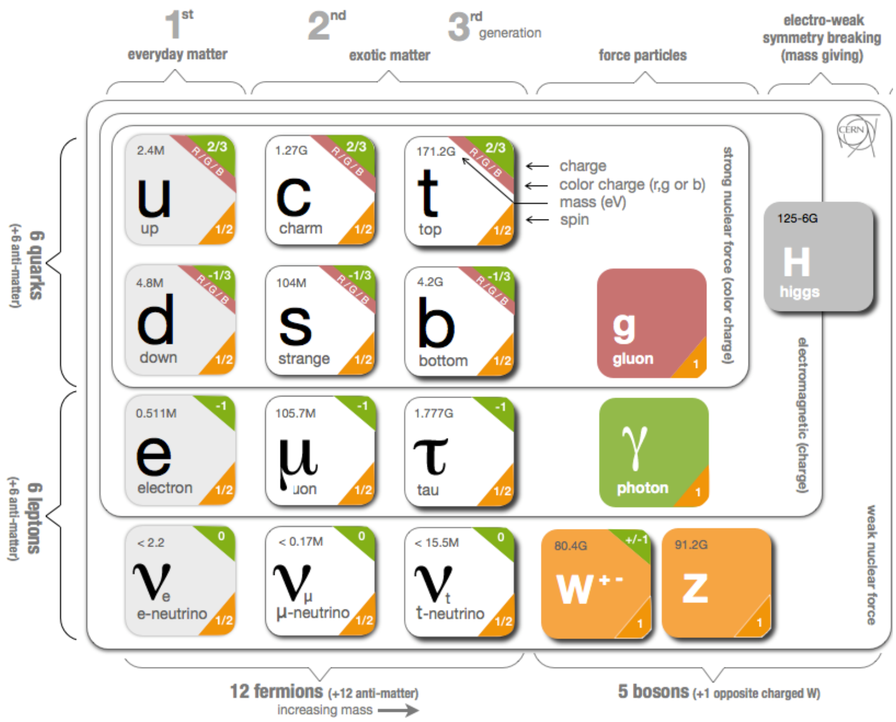
Abstract

Paper for the Comprehensive Exam.

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 the particles shown are discovered at the moment and no other fundamental particle is discovered. Source of picture: [9]

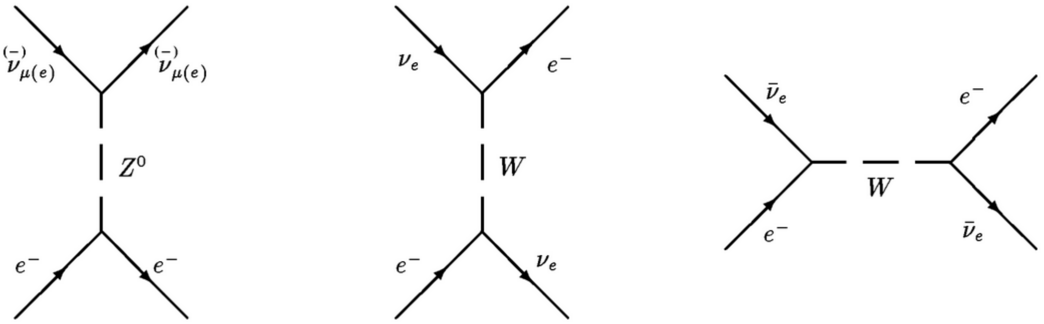


1 Introduction. Neutrinos as Fundamental Standard Model Particles

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, 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 interactions, through exchange of gluons. All those particles and also neutrinos can interact through weak interactions which include charged current (CC) interactions, through W-boson, and neutral current (NC) interactions, through 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. However, neutrinos also exist in the nature and there are many of them. Quoting [2], 11.1: "John Bahcall, who was responsible for most of the calculations of solar neutrino abundances, liked to say that 100 billion neutrinos pass through your thumbnail every second; and yet they are so ethereal that you can look forward to only one or two neutrino-induced reaction in your body during your entire lifetime".

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



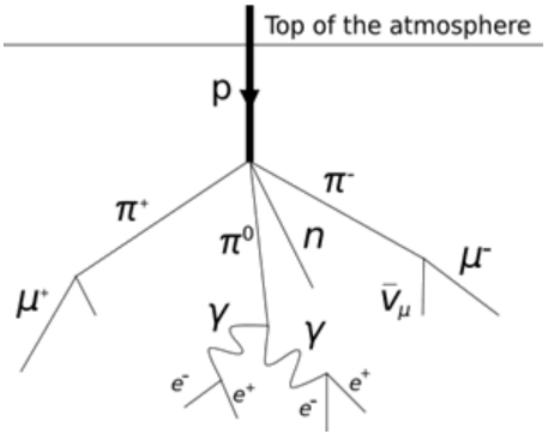


Figure 3: Cosmic shower induced by scattering of the incident cosmics proton of an air molecule. Charged and neutron pions are born in the reaction and then they further decay as $\pi^0 \to \gamma\gamma$, $\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \bar{\nu_\mu}$.

Two very common and well known interactions which includes neutrinos are neutron beta decay and muon decay. The Feynmann diagrams of these processes are shown at **??**. Mean lifetime of free neutron is 15 minutes and $> 99.9\%$ of those which decay will do it though the beta decay: $n \to p + e^- + \bar{\nu_e}$ [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-quark 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 ${}^{49}{}_{19}K \to {}^{40}{}_{20}Ca$, ${}^{64}{}_{29}Cu \to {}^{64}{}_{30}Zn$, ${}^{3}{}_{1}H \to {}^{3}{}_{2}He$ [2] (the positive beta decay, $p \to n + e^+ + \nu_e$, is not possible for free proton but it can happen when the proton is the part of the nuclei). As for the muon, it's mean lifetime is $2\mu s$ and 99% of muons which decay would do that to electron, nuom neutrino and electron antineutrino as $\mu^- \to e^- + \nu_\mu + \bar{\nu_e}$ though the the W boson. This process is also common in nature, in cosmic rays: muon are produced in the upper layers of the Earth atmosphere from the interaction of the particles coming from cosmics with the atmosphere molecules though the reaction, for instance, $p + p \to n + p + \pi^+$ 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. 3.

There are three flavors of neutrino, one for each generation: electron neutrino, muon neutrino, tau 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.

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

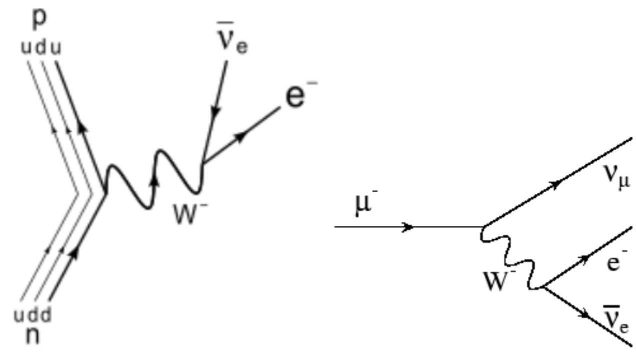


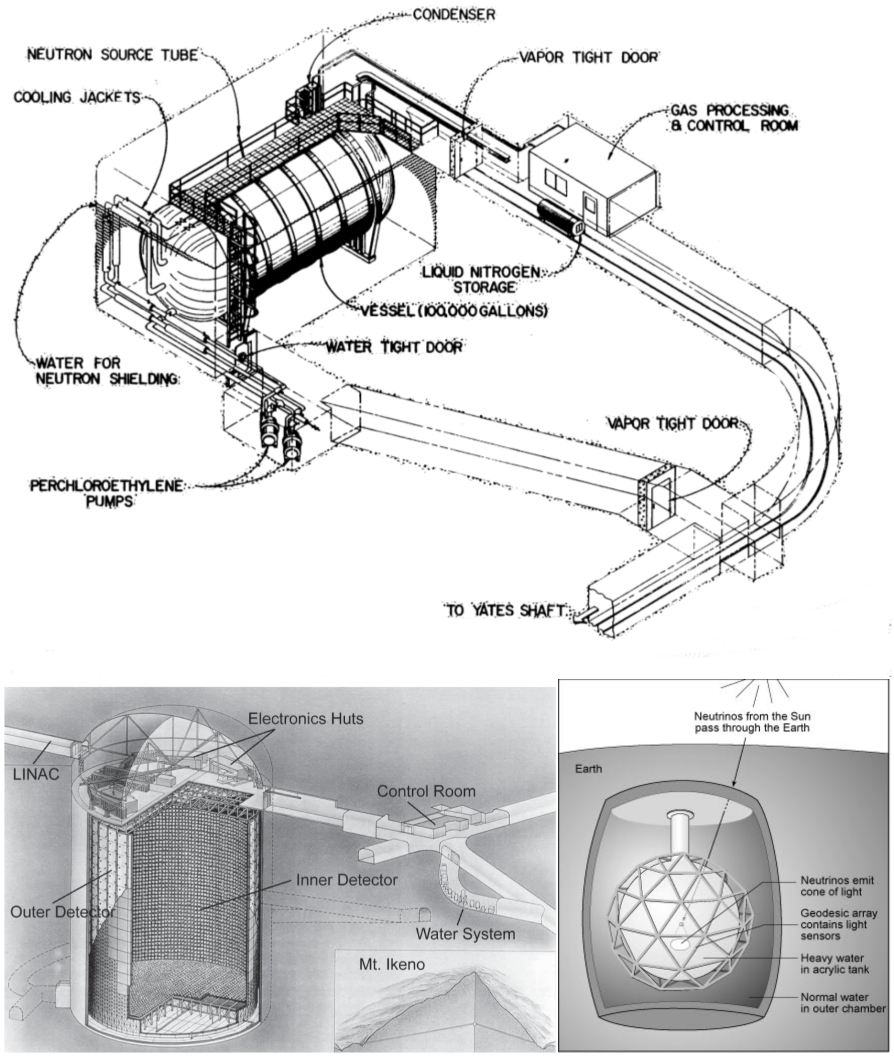
Figure 4: Feynmann diagrams of (left) neutron and (right) muon decays. Neutron beta decay [11](d-quark of transfers to u-quark through the W-boson with emission of electron and antineutrino). Muon decay [10](muon decays to electron, neutrino and antineutrino through W-boson

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

This paper reviews the main idea which stands beyond the neutrion oscillations from the theoretical point of view and the related experimental measurements. Section [REFERENCE] gives theoretical derivation of the neutrino oscillations phenomenon for the two neutrinos case, introduces the mixing matrix and lists the its parameters. Section [REFERENCE] reviews the parameters which already has been measured in variety of neutrino experiments and which questions are still open. Section [REFERENCE] discusses the physical program and the technical charasteristics of the future experiment - the Long Beamline Neutrino Facility which is under construction in Fermilab now and is going to be one of the most important concentrations for the Fermilab and for the whole USA and Worldwide experimantal particle physics program in the nearest future.

Figure 5: Schemes of the Solar neutrino experiments: Homestake Experiment, Super Kamiokande and Sudbury Neutrino Oscillations



2 Neutrino Oscillations. History and Status

2.1 First Discovery and Confirmation

History of the discovery of these phenomane is described in [2], chapter 11. The first evidence of the neutrino oscillations had place in the Ray Davis's 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 in 2001 by Super-Kamiokande collaboration. This experiment used water detector and could register any sort of neutrino though 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.

2.2 Neutrino Detection Techniques

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 tau-neutrino is energetic enough - $\tau^{\pm}$). The properties of charged lepton can be measured in the detector and then from momentum and energy conseravation 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 tau-neutrino can only produce tau-lepton). The wikipedia page of Neutrino Detectors list the main detection techniques which make possible to register neutrinos [8]:

- 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 south dakota experiment: neutrino interacted with chlorine-37 atom and converted it to argon-37. Then argon atoms were separated and counted. The experiment was the first to indicate the Solar Neutrino Problem. 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. In general, this is threshold type of detection - particle is either detected or not. However, by having several layers with different n (refractive index), it's possible to differentiate charged particles by velocities better. Common working substance for Cherenkov detectors in neutrino physics are ice, water and heavy water.

- Tracking calorimeters. For high energy neutrinos, neutral current weak interactions cause hadronic shower and charged current weak interactions cause electromagnetic shower. The showers produced by charged particle (product of original neutrino nteraction) identify track parameters, momentum and energy of charged particle.

2.3 Neutrino Oscillations

Lets consider two neutrinos case as it's described in Griffiths[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,
$\nu_1(t) = \nu_1(0)e^{\frac{-iE_1t}{h}}$, $\nu_2(t) = \nu_2(0)e^{\frac{-iE_2t}{h}}$
Suppose, at t=0 there were $\nu_e(0) = 1$, $\nu_\mu(0) = 0$
Then $\nu_1(0) = -sin\theta$, $\nu_2(0) = cos\theta$, $\nu_1(t) = -sin\theta e^{\frac{-iE_1t}{h}}$, $\nu_2(t) = -cos\theta e^{\frac{-iE_2t}{h}}$
Thus, we are getting the system:
$-sin\theta e^{-\frac{iE_1t}{h}} = \nu_\mu(t)cos\theta - \nu_e(t)sin\theta,$
$-sin\theta e^{-\frac{iE_2t}{h}} = \nu_\mu(t)sin\theta - \nu_e(t)cos\theta$
By solving this sytem for ν_e and ν_μ, one would get
$P_{\nu_e\to\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2,$
$P_{\nu_e\to\nu_e} = |\nu_e(t)|^2 = 1 - [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2$
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
$P_{\nu_e\to\nu_\mu} = |\nu_\mu(t)|^2 = [sin2\theta sin\frac{(E_1-E_2)t}{2h}]^2,$

Three neutrino case is described in the "Long-baseline Neutrino Oscillation Physics" section of the draft Conteptual Design Report of the 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:

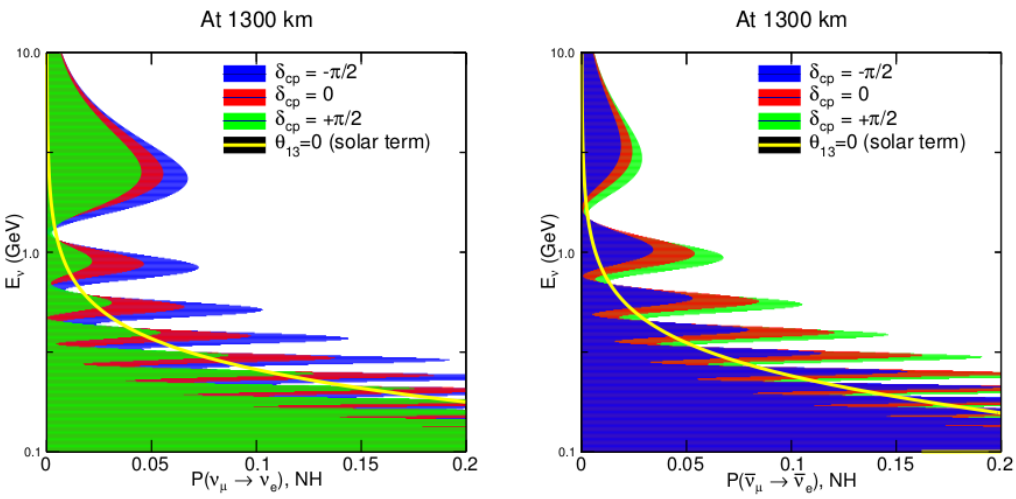
$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & e^{i\delta_{CP}}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}s_{13} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

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 sqares of masses differences: $\Delta m^2_{12} = m^2_1 - m^2_2$ and $\Delta m^2_{32} = m^2_3 - m^2_2$. Mass differences were measured in other neutrino oscillation experiments but the Δm^2_{12} and Δm^2_{32} 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 Δm^2_{12} and Δm^2_{32} 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, CabibboKobayashiMaskawa (CKM) matrix, is much more diagonal:

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[14]

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

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

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

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 DUNE's baseline is 1300 km and it's expected to be enough to determine the neutrino mass hierarchy and also the CP-violation phase.

The figure6 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)

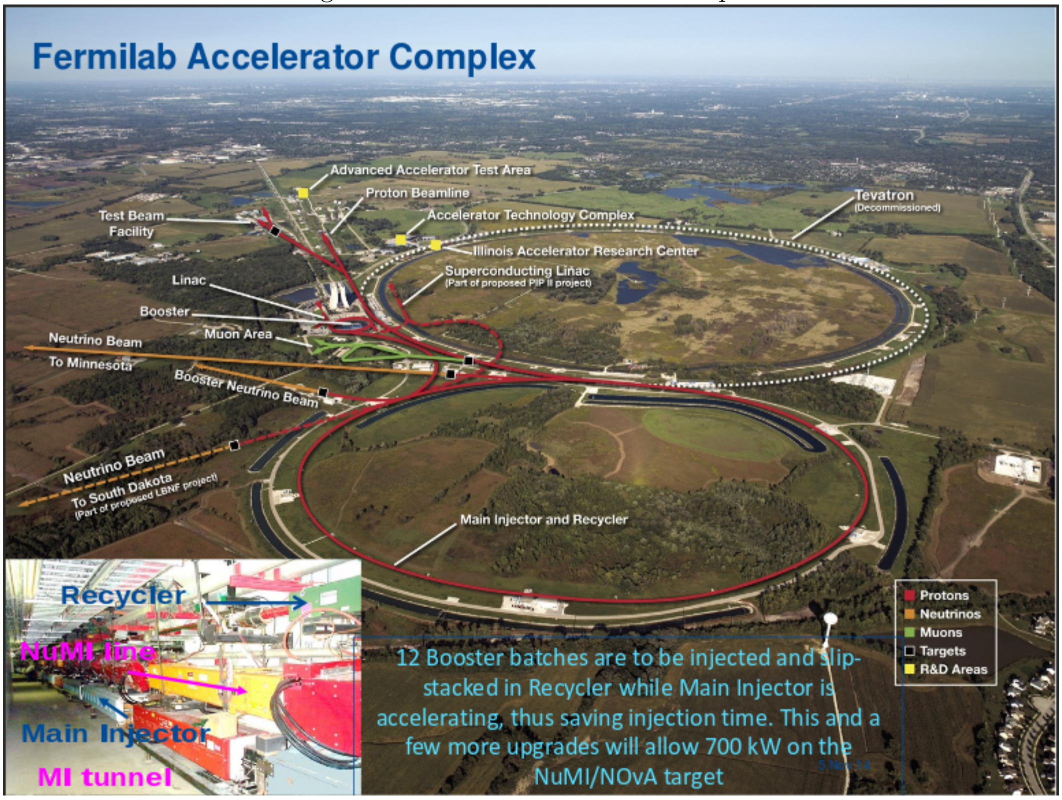
Section 14.5 in [REFERENCE] describes measurements of Δm^2_A and θ_A, splitting between atmospheric neutrino and accelerator experiments results. Section 14.6 reviews measurements of θ_{13} which was measured recently.

According Particle Data Group Review **??** 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 measurements of already measured mixing matrix parameters θ_{12}, θ_{23}, θ_{13}, $\Delta m_{12}{}^2$, $|\Delta m_{31}{}^2|$ are part of new neutrino experiments physics programs.

Figure 7: Fermilab Accelerator Complex



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

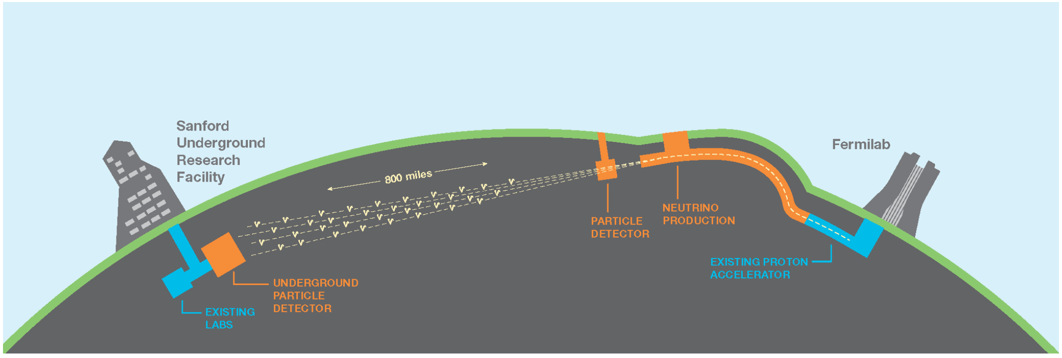
The Long Beamline Neutrino Facility is the facility being internationally designed for the future Deep Underground Neutrino Experiment (DUNE) which has wide physics program for variety of precision measurements and searches beyond the Standard Model. The general scheme of the facility is shown on figure 8. This section gives more details on neutrino beam production and the detector descriptions. The information if taken mostly from the LBNF website [12] and the Conceptual Design Report which is currenly under development but drafts are partially available [13], [14]. 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 CDR drafts and the main pages of the LFNF website.

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 [13].

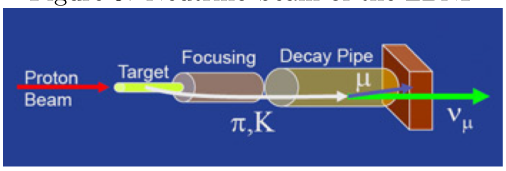
- neutrino beam of high intensity which would be able to produce large amount of neutrinos to be registered at the far site

Figure 8: Long Baseline Neutrino Facility



The neutrino flux will be produced using existing proton accelerator in Fermilab. Then neutrinos will be registered by near detector, travel 800 miles through the Earth mantle to the Sanford Underground Research Facility in South Dakota and be registed by far detector. [12]

Figure 9: Neutrino beam of the LBNF



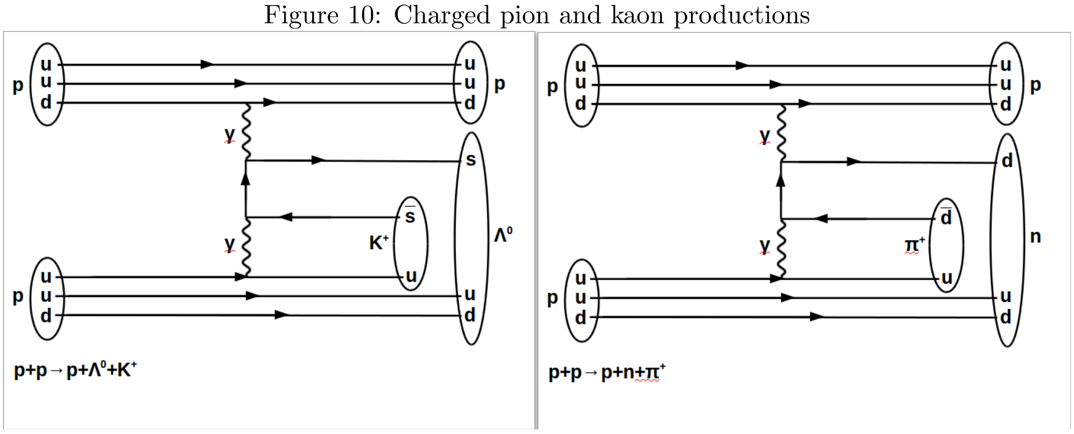
The neutrino beam production at Long Beamline Neutrino Facility. [12]

- 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)

3.1 Neutrino Beam

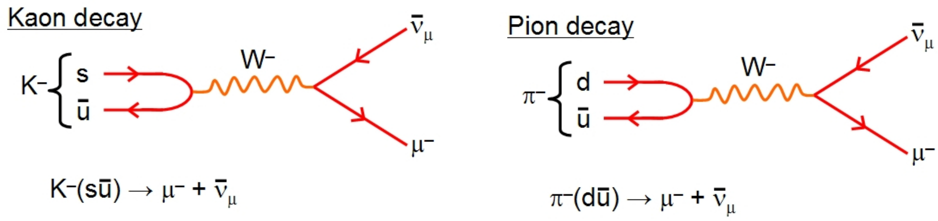
It's going to use the highest intensity neutrino beam ever created. The proton accelerator in Fermilab which was already used in other experiments in Fermilab before will produce the beam of protons. Then protons will hit a target and create kaons and pions through the same reactions as take place in 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

Figure 10: Charged pion and kaon productions



Exmples of Feynmann diagrams of chagred kaons and pions production in proton-proton scattering.

Figure 11: Charged pion and kaon decays



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

quark from the accelerator beam proton scatters on the other quark from the proton or neutron of the target substance. 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 $s\bar{s}$ 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 $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu_\mu}$, $K^+ \to \mu^+\nu_\mu$, $K^- \to \mu^-\bar{\nu_\mu}$. The branching ratios of charged pions and kaons to decay into $\mu^+\nu_\mu(\mu^-\bar{\nu_\mu})$ are $(> 99.9)\%$ and $(63.55 \pm 0.011)\%$ respectively 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, but the focusing is being done with the certain configuration of the magnetic field and thus only charged particles can be focused. Neutral pions, π^0s, are very likely to be produced as well but they decay as $\pi^0 \to \gamma\gamma$ and thus can't contribute to the neutrino production.)

After being produced in the rections described above, the neutrinos will be detected in the close detector in the Fermilab. Then the neutrinos will travel 800 miles underground 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 tuned the lower primary proton momenta down to 60 GeV/c must present
- the systematic error to the parameters of the neutrino flux must be reduced
- 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 Conceptual Design Report [REFERENCE] 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^0_S and Λ in the NC and CC
- nucleon structure, parton distribution functions and QCD studies
- neutrino-argon interactions and nuclear effects
- 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. 4, middle and right) and measure the products of these interactions μ^-, μ^+, e^-, and e^+. (While the production 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 which will help with CP-violating phase measurement. 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 [12], "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."

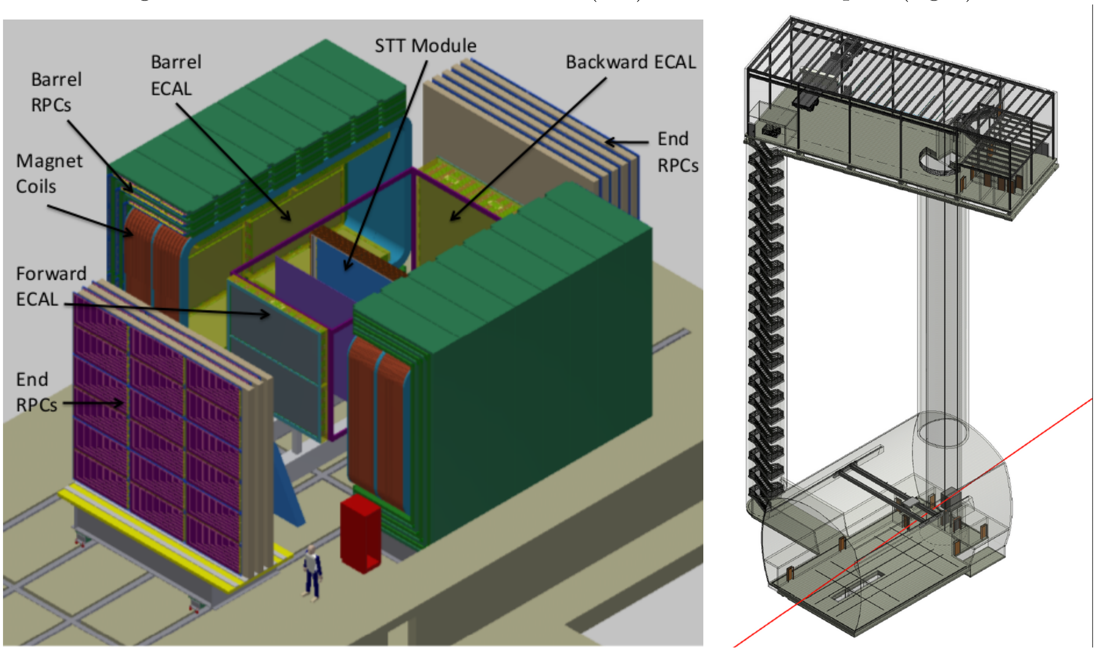
3.3 Far Detector

That's how the LBNF website describes the far detector [12]: "The DUNE far detector will consist of four modules, each of which will be housed in a cryostat containing 17,000 metric tons of liquid argon target material. LBNF will excavate and provision a set of four caverns 5,000 ft (1500 m) underground arranged as a pair of double caverns, in which to place them. The double caverns, aligned parallel to the beam, will each have 50 ft (15 m) of rock separating two end-to-end modules. A fifth cavern, between the pair, will house the cryogenics equipment."

LBNF will provide the cryostats as well as the cryogenics equipment that is used to maintain the argon in the liquid state and to keep it pure and circulating smoothly during operations.

The Far Detector consists of

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



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

The TPC is particle identification system of the detector. The chamber is merged into the liquid argon at tempetature of 89 K. On the figure **??** 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 unifoem electric field between anode and cathod planes. Chargedparticle traveling though 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
- 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 long baseline neutrino experiments KEK [19], NuMI [20], CNGS [21] and J-PARC [22]. The main parameters, compared to the LBNF parameters, are summarized in the table 3.

Figure 13: Sanford Underground Research Facility (SURF)

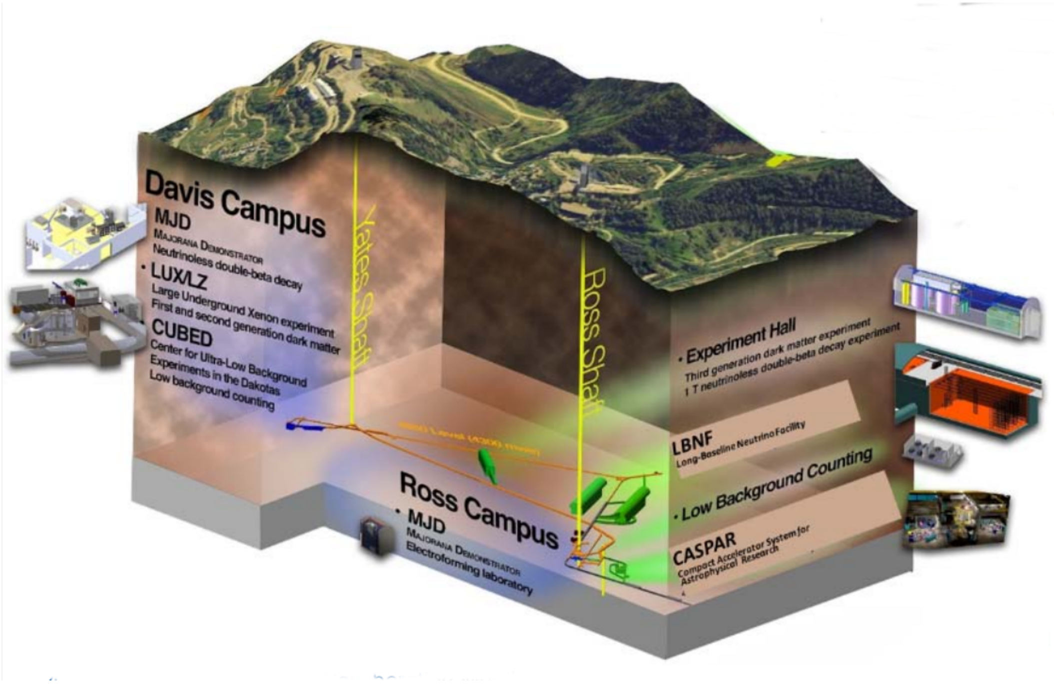
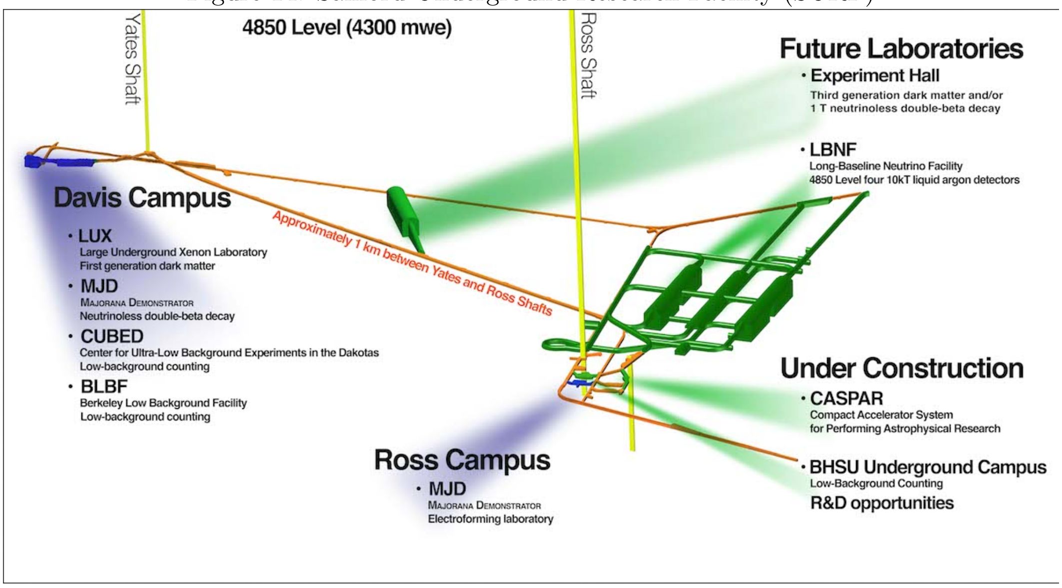


Figure 14: Sanford Underground Research Facility (SURF)



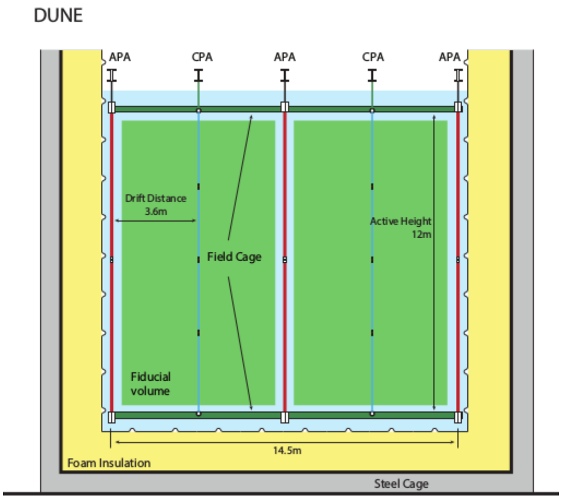


Figure 15: The scheme of the cross section of the LArTPC for far detector of the DUNE. Source of figure: [13]

Table 3: Comparison of different long baseline neutrino oscillations experiments

	KEK (K2K)	NuMI	CNGS	T2K	LBNF (DUNE)
location					Illionois - South Dakota (USA)
accelerator accelerator					Fermilab accelerator complex
time of operation					future
beam power	5 kW	300-350 kW	300 kW	750 kW	
energy of protons	12 GeV	120 GeV	400 GeV	30 GeV	
baseline	250 km	735 km	730 km	295 km	1300 km
near detector(s)					near DUNE; fine-graned detector
far detector(s)					far DUNE; liquid Argon detector

4 Conclusions

The DUNE's baseline is 1300 km and it's expected to be enough to determine the neutrino mass hierarchy and also CP-violation phase. These two important neutrino mixing parameters were never measured before.

However, the LBNF will not be able to measure the neutrino masses themselves - neutrino oscillations are only sensitive to differences. Neutrino mass measurement require different kind of experiments - for example, studiyng high energy cut-off on the electron energy spectrum in beta-decay of tritium but so far all the experiments trying to measure it were able only to set limits on neutrino masses ([2], 11.4).

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[19] KEK

[20] NuMI

[21] CNGS

[22] J-PARC