Physics Sensitivty Studies At The Long Baseline Neutrino Experiment

A Project Report
Submitted for the Degree of
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by

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CERTIFICATE

This is to certify that the work contained in this project entitled **Physics Sensitivty Studies At The Long Baseline Neutrino Experiment** submitted by **Baishali Dutta**, student of M.Sc. in Physics (final year), Roll No. - 122121007, Department of Physics, Indian Institute of Technology Guwahati, has been carried out under my supervision.

Date: 16th Apr,14
Place: IIT Guwahati

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DECLARATION

This is to declare that the work contained in this project entitled **Physics Sensitivty Studies At The Long Baseline Neutrino Experiment** is carried out by me under the guidance of Dr. Bipul Bhuyan in the department of Physics, Indian Institute of Technology Guwahati.

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Abstract

With the discovery of atmospheric neutrino oscillation at Super-Kamiokande, the scope of physics, beyond the Standard Model, has become a central point for exploration. After years of data collection from atmospheric, solar, reactor, supernovae and few long baseline (LBL) experiments, most of the neutrino flavor mixing parameters are being measured with great precisions. But these are not sufficient to determine the ones that are yet to be known such as CP violation phase (δ_{CP}), mass hierarchy (sign of Δm^2_{31}). An advancement in Intensity Frontier Research with high intensity accelerator generated neutrino beams are needed to complete our understanding of neutrino flavor mixing.

Long Baseline Neutrino Experiment (LBNE) - a future proposed experiment at Fermilab, with world's highest intense neutrino beam, is aimed to investigate and determine the characteristic oscillation parameters, leptonic CP violation phase and relative mass ordering of neutrinos. In the designing period of LBNE, throughout my thesis work, a simulation study has been carried out to analyse the expected performance and potential of the future experiment.

The simulation process has been done by using the GLoBES (General Long Baseline Experiment Simulator) package which allowed us to demonstrate the demanded outcomes, by studying the sensitivity reach of the proposed Long Baseline Neutrino experiment. During my work, GLoBES has been employed to unveil the full potential of LArTPC technology proposed as the Far Detector placed underground at Homestake mine, 1300 km away from the main injector at Fermilab.

1 Introduction

In the way of exploring the origin of universe, neutrinos are found to be the most mysterious particle ever discovered. Our entire knowledge of the base of matter relies on the Standard Model of Particle Physics. But the discovered property of flavor conversion of neutrinos cannot be explained by the Standard Model theory which enforces the requirement of its modification.

During the last decade, the study of neutrino oscillation which occurs due to the mixing of the weak eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ and the mass eigenstates(ν_1, ν_2, ν_3), has entered a revolutionary era with the discovery of the third non-zero mixing angle θ_{13} at a confidence level greater than 5σ[1]. With the conclusive evidences of non-zero θ_{13} from Daya Bay, RENO reactor experiments as well as previous LBL experiments such as MINOS, Double Chooz, T2K, the parameter stands at $\sin^2 2\theta_{13} \approx 0.1$[2]. Measurement of non-zero θ_{13} allows us to study the possibility of existent CP violation in leptonic sector by investigating CP violation phase δ_{CP}, the last unknown mixing parameter of Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. The accurate determination of δ_{CP} is not possible without answering the mass hierarchy (sign of Δm^2_{31}) issue[1].

Long Baseline Neutrino Experiment (Fermilab) is aimed to measure the oscillation parameters with significant precision, study the leptonic CP Violation and the mass hierarchy. The experiment will be started with the conventional beam power of 0.7MW, later on which can be intensified to 2.3MW with Project X (proposed proton accelerator complex at Fermilab) along with 1300 km long baseline.

Using GLoBES as a simulation tool, a focussed study on the preliminary investigation of the ability to measure the fundamental neutrino mixing parameters and resolving the intrinsic degeneracies, has been done based on the experiment attributes. The thesis is organised to cover a theoretical overview of neutrino oscillation physics, used LBNE beam profile, experimental setups and an overall sensitivity analysis using GLoBES to outline the expected performance of the experiment[3][4].

2 Theoretical Motivation

2.1 What is Neutrino?

> **Neutrino is the most tiny quantity of reality ever imagined by human being - F. Reines.**

Among all the fundamental particles of our universe neutrinos, the so called ghost particles, are the least understood particle. According to Standard Model, twelve particles are the base of matter. Six quarks: up, down, charm, strange, top and bottom quark and six leptons: e^- , μ^-, τ^- and three neutrinos (ν_e, ν_μ, ν_τ). Each charged lepton is always being associated with its corresponding neutral neutrino.

2.2 Discovery

The existence of neutrino was first predicted by Wolfgang Pauli in 1930 to rescue the endangered conservation laws in nuclear beta decay. When a parent nucleus decays into a daughter nucleus with emission of an electron, the energy of the emitted electron should be fixed. But experiments showed a continuous energy spectrum which violates the universal conservation laws of energy and momentum. Pauli suggested that the total energy is being carried out by the electron and an associated neutral particle (Neutrino). We know now that the particle coming out in the nuclear beta decay process with electron is an anti-neutrino.

$$\mathrm{X(A,Z)}\rightarrow\mathrm{Y(A,Z\text{-}1)}+e^-+\bar{\nu_e}$$

After 26 years of its prediction, existence of neutrino (ν_e) was experimentally verified by F. Reines and C. Cowan in 1956 in the Inverse-Beta decay process[5].

$$\bar{\nu_e} + \mathrm{p} \rightarrow \mathrm{n} + e^+$$

2.3 Unique Features of Neutrinos

Neutrinos are neutral and the lightest leptons (spin 1/2 particle). They exist in three flavors (ν_e, ν_μ, ν_τ). Though in Standard Model neutrinos are considered to be massless particle, the small but non-zero mass ($<10^{-6}m_e$) of the neutrino is now experimentally verified which helps us to explain the observed flavor oscillation.

Neutrinos of a particular flavor can oscillate into other flavors without any external influence. It was Ray Davis's and John N. Bahcall's Homestake Experiment which had first measured the deficiency of the solar neutrino fluxes (Solar neutrino problem) from the theoretically predicted flux rates using a chlorine-based detector. But the confirmed result came fron Sadbury Neutrino Observatory in 2001. SNO detected the ν_e fluxes coming from the sun and distinguished them from other flavors by using a heavy water detector.

Neutrino does not participate in strong interaction, it interacts only via weak interaction. Being a neutral particle electromagnetic force has no influence and due to negligible mass gravitation force also has no impact on it.

Helicity of a particle is defined by the projection of spin along its momentum direction. From Goldhaber's helicity measurement experiment of neutrinos (1957) it was found that neutrinos are left handed (H=-1) while antineutrinos are right handed (H=+1).

2.4 Widespread Neutrinos

Neutrinos are omnipresent. Every second about 100 trillion neutrinos pass through our human body. Sources of neutrinos can be characterized in two categories - Natural Sources and Artificial Sources[5][6].

Natural Sources:

- **Solar Nutrinos($\sim$1 MeV):** Sun is the biggest source of neutrinos.
- **Atmospheric Neutrinos ($\sim$1 GeV):** Neutrinos produced in the atmosphere.
- **Supernovae Neutrinos ($\sim$10 MeV):** Neutrinos that are coming from supernovae such as SN 1987A.
- **Geo Neutrinos ($\sim$0.1 MeV):** Neutrinos from earth.
- **Relic Neutrinos ($\sim 10^{-4}$ eV):** Neutrinos from cosmic bigbang background.

Artificial sources:

- **Reactor Neutrinos ($\sim$1 MeV):** Neutrinos coming from reactor sources.
- **Accelerator Neutrinos ($\sim$MeV-TeV):** Neutrinos produced from man-made accelerators.

2.5 Impacts on Research

- **Particle Physics:** Evidences from neutrino oscillation phenomenon has opened the door for exploring physics beyond Standard Model.
- **Nuclear Physics:** Due to tremendous penetrating power, neutrinos can be used to elucidate nuclear structure.
- **Cosmology:** Neutrinos can be used to explain nucleosynthesis, dark matter problem, matter-antimatter asymmetry.
- **Astrophysics:** To analyze stellar activity at deep inside the stars, energetic of stars and supernovae, neutrinos are very powerful hope.

2.6 Undetectable Neutrinos

Neutrinos are weakly interactive which allows them to pass through the whole world without any deviation as the mean free path of neutrinos is several light years. Because of their neutrality they are not influenced by the electromagnetic interaction and smallness of their mass makes them unaffected by the gravity. Because of very small interaction cross-section, direct measurement is very difficult. They are mostly be observed by indirect detection through their corresponding charged leptons.

Neutrinos can interact mainly through charged and neutral current interaction.

Neutral Current Interaction: It is mediated by the exchange of Z boson. In this process neutrino can transfer some of its energy and momentum to the target particle of the medium. If the target particle is charged and light weight, it can obtain a high speed emitting Cherenkov radiation which can be directly measured but the flavor information of the neutrino will be lost in this way.

Charged Current Interaction: It is caused by the exchange of charged W boson. Neutrino in this case creates its partner charged lepton if and only if the energy of it would be sufficient to create its partners mass. The partner lepton can be detected which will give us the information of the neutrinos flavor.

Cross-sections corresponding to the charged current neutrino-nucleon interactions is of the order of 10^{-31} cm^2/GeV which is almost double to that of the antineutrino cross-sections. Also, neutral current cross-sections are small enough compared to its charged current counterparts but not negligible [10].

2.7 Massive Neutrinos and Their Oscillation

2.7.1 Mass Hierarchy

Neutrino flavor mass is determined by the contribution of three mass eigen values (m_1,m_2,m_3) corresponding to three mass eigen states(ν_1,ν_2 and ν_3). From experimental aspects we can only measure the flavor states not the mass states of neutrinos and from oscillation probability the mass squared difference (Δm^2). According to our current knowledge $m_2 > m_1$ and the difference between them is small as the experimental outcome of Δm^2_{21} is positive and small. But experimental measurements showed that mass squared difference between m_2 and m_3 is quite large and as the exact value of the masses are not known i.e we do not know whether m_3 is smaller or larger than m_1 and m_2. This leads to the hierarchy of neutrino mass having two possibilities: m_3>m_2>m_1 which is called normal hierarchy while m_2>m_1>m_3 called inverted hierarchy. Both normal and inverted hierarchy and the proportions of the mass eigen states in a particular flavor are depicted in Figure 1.

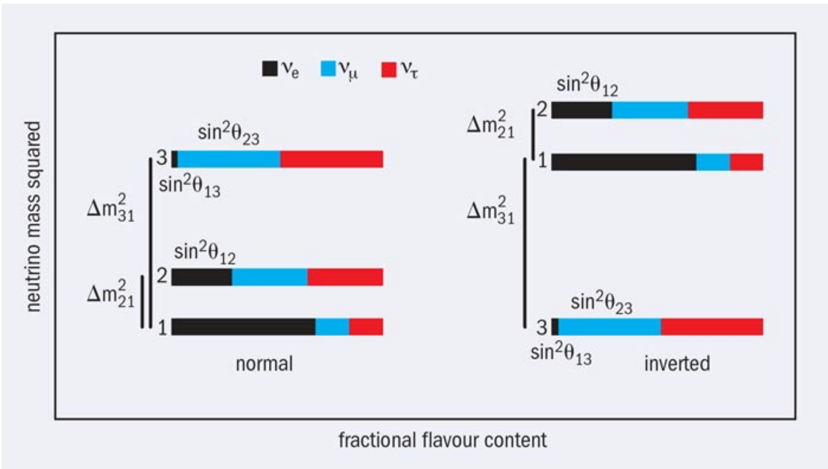

Figure 1: Credit: CERN Courier (April 27, 2012)

2.7.2 Oscillation Physics

A neutrino produced with a fixed flavor can change its identity while traveling i.e it can be transformed into another flavor. The idea of oscillation was put forward by Pontecorvo in 1957[5] (ν_e-$\bar{\nu_e}$). Flavor transition was first considered by Maki, Nakagawa and Sakata in 1962[6].

Flavor of neutrino is not fixed as it is determined by a linear combination of three mass eigen states. Neutrino produced in a particular flavor propagates through the medium as mass eigen states of oscillating amplitude which causes the flavor conversion. The mixing between mass and flavor eigen states of the neutrinos are determined by the mixing angles [5].

Mathematically it is described below: $|\nu_a\rangle$=$U^*_{ai}|\nu_i\rangle$

The flavour eigen states on the L.H.S is related to the mass eigen states on the R.H.S by a unitary transformation. For 3-flavour mixing summation of i extends over 1,2,3.

2.7.3 2-Flavor Oscillation

The simplest case of neutrino oscillation is to consider the oscillation between two neutrino species for example electron and muon neutrino. For two-flavour oscillation only two mass eigen states have been considered.
The unitary matrix U that transforms the flavor states to mass states is given by

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Here θ is the mixing angle between the two neutrinos considered.

2.7.4 Oscillation Probability In 2-Flavor Scenario

Let us consider that a source is producing a particular flavor of neutrino flux say ν_e.The probability that another flavor say ν_μ can be detected at the detector placed at some distance(L) is given by

$$\text{P}(\nu_e \rightarrow \nu_\mu;\text{L})=\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Where Δm^2 in eV^2, L is in km and E in GeV or L is in m and E in MeV.

2.7.5 Survival Probability In 2-Flavor Scenario

Probability of detecting the initial flavor at the detector is called survival probability given by

$$\mathrm{P}(\nu_e \rightarrow \nu_e;\mathrm{L}) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

2.7.6 3-Flavor Oscillation:

In case of 3-flavor oscillation, 2-flavor oscillation can be generalized with the introduction of a CP violation phase.

2.7.7 CP Violation Phase (δ_{CP}):

CP violation is basically the violation of charge conjugation and parity symmetry. The so called CP Symmetry is the combined symmetry operation of charge conjugation and parity operation. This states that physics laws should remain same if we interchange the particle with its own anti-particle[2].

Neutrino mixing matrix U depends on the mixing angles as well as phases. If N be the no. of neutrino species then

$$N_{angles} = \tfrac{1}{2}\mathrm{N(N-1)}\ ,\ N_{phase} = \tfrac{1}{2}\mathrm{(N-1)(N-2)}$$

So, if N=2 i.e 2-flavor oscillation,

$$N_{angles} = \tfrac{1}{2}2(2\text{-}1) = 1 \text{ and } N_{phase} = \tfrac{1}{2}(2\text{-}1)(2\text{-}2) = 0$$

CP violation phase occurs if we consider 3-flavor oscillation i.e N=3. In this case,

$$N_{angles} = \tfrac{1}{2}3(3\text{-}1) = 3 \text{ and } N_{phase} = \tfrac{1}{2}(3\text{-}1)(3\text{-}2) = 1$$

Because of this non-zero phase δ mixing matrix U is no longer real valued for 3-flavor case.

PMNS Matrix

For 3-Flavor case the unitary matrix U that transforms the flavor states to mass states is named after Pontecorvo, Maki, Nakagawa and Sakata, called PMNS matrix[2].

$$\begin{pmatrix} C_{21}C_{13} & S_{21}C_{13} & S_{13}e^{-i\delta} \\ -S_{21}C_{32} - C_{21}S_{32}S_{13}e^{i\delta} & C_{21}C_{32} - S_{21}S_{32}S_{13}e^{i\delta} & S_{32}C_{13} \\ S_{21}S_{32} - C_{21}C_{32}S_{13}e^{i\delta} & -C_{21}S_{32} - S_{21}C_{32}S_{13}e^{i\delta} & C_{32}C_{13} \end{pmatrix}$$

Here, $S_{jk} = \sin\theta_{jk}$ and $C_{jk} = \cos\theta_{jk}$. The mixing matrix is governed by four angles ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)and two mass squared differences (Δm^2_{21} and Δm^2_{32}). It is evident from the PMNS matrix that $e^{\pm i\delta}$ always accompanies with S_{13}. So, if θ_{13} =0 , S_{13} =0 and hence mixing matrix is real valued.

3 Current Status of Neutrino Physics

Neutrino experiments can be approximated to have only 2-flavor like oscillation instead of full 3-flavor treatment in the limit $|\Delta m^2_{32}| \gg |\Delta m^2_{21}|$. First successful observation of neutrino oscillation phenomena was established by Super-Kamiokande experiment in 1998. Later in 2002, SNO collaboration also approved the same in solar neutrino sector.

3.1 Atmospheric Neutrinos

The first convincing evidence of neutrino oscillation was provided by Super-Kamiokande where an angular dependency of atmospheric neutrino events were recorded. Atmospheric neutrinos are produced by the interaction of primary cosmic rays with the atmosphere at a height around 10 to 20 km above Earth's surface. The production process is as follows[1]:

$$\begin{aligned} p^+ + \text{ AtomicNucleus } &\to \pi + \text{ FurtherHadrons} \\ \pi &\to \mu + \nu_\mu \\ \mu &\to e + \nu_\mu + \nu_e \end{aligned}$$

Therefore, initially the atmospheric neutrino flux consists of $\nu_\mu, \bar{\nu_\mu}, \nu_e, \bar{\nu_e}$ in a ratio $(\nu_\mu + \bar{\nu_\mu})/(\nu_e + \bar{\nu_e}) \approx 2$. Super-Kamiokande can detect neutrino interactions through cerenkov radiation emitted by secondary particles. It can separate ν_μ and ν_e but it does not have the capability to distinguish between ν and $\bar{\nu}$ as well as to detect ν_τ. The detection in Super-Kamiokande detector is in agreement with $\nu_\mu \to \nu_\tau$ oscillation. The oscillation in $\nu_\mu \to \nu_\tau$ channel was also confirmed by K2K accelerator experiment.

The amospheric data provides $\to$

$$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3} eV^2 \text{ and } \sin^2 2\theta_{23} > 0.95 \text{ (90 \% CL)}$$

3.2 Solar Neutrinos

Our sun is an intense source of electron neutrinos and the basic reaction of producing neutrinos during nuclear fission is as follows :

$$4p + 2e^- \to^4 \text{He} + 2\nu_e + 26.73 MeV$$

In 2002, SNO collaboration experimentally verified that the deficit in the ν_e flux caused due to the oscillation into other flavors. The reactor data from

KAMLAND also observed the same. Results from these experiments provide the solar mixing parameter as[1]

$$|\Delta m^2_{\odot}| = (7.59 \pm 0.21) \times 10^{-5}\mathrm{eV}^2$$
$$\text{and } \tan\theta_{\odot}{}^2 = 0.47^{0.06}_{-0.05}$$

Dominating mass eigenstates in case of solar neutrinos are ν_1 and ν_2 where $m_2{>}m_1$. So, solar mixing parameters are basically the measure of Δm^2_{21} and $\tan^2\theta_{12}$.

3.3 Unknown

Solar and atmospheric neutrino experiments provided the measure of $|\Delta m^2_{32}|$, Δm^2_{21}, θ_{12} and θ_{23}. But currently mass hierarchy (Normal: $m_3{>}m_1$ or Inverted: $m_3{<}m_1$) of neutrino mass eigen states are not known as well as there is no constraint on CP violation phase δ_{CP}. According to Dec, 2013 result of T2K experiment the best fit value for $\sin^2 2\theta_{13}$ is[19]:

$$\sin^2 2\theta_{13} = 0.14^{0.038}_{-0.032} \text{ [NH]}$$
$$\sin^2 2\theta_{13} = 0.17^{0.045}_{-0.037} \text{ [IH]}$$

4 Long Baseline Neutrino Experiment

4.1 Introduction

Long Baseline Neutrino Experiment is a proposed future experiment expected to be started in 2022 at Fermilab to investigate the unknown neutrino oscillation parameters, leptonic CP violation phase δ_{CP} and the neutrino mass ordering (mass hierarchy). Over the last few decades neutrino physics became the heart of intensity frontier research field as neutrinos are the most rarely interacting particles. Neutrinos can travel through the whole world without even interacting with a single atom. So, to increase chance of getting significant trace of neutrinos, we need a large target material for their detection as well as a highly intense neutrino beam. LBNE is designed to fulfill both the aspects.

4.2 Strategy

LBNE has been planned to send world's highest intense neutrino beam 1300 km long baseline through Earth's mantle from Fermilab to an advanced far detector placed at Sanford underground laboratory [14][15][16]. A large amount of target material will be used as a far detector to collect the signal originated from neutrino interactions with the detecting material.

Aim of this experiment is not only to complete the neutrino physics by investigating the unknown facts of this field of research as well as to understand the scope of physics beyond the Standard model and existing matter-antimatter symmetry of our universe.

4.3 Beamline

An intense proton beam extracted from a proton source will be colliding with a near target material which in turn produce short-lived secondary hadrons such as kaons, pions etc. The hadrons produced through secondary interaction are then focussed by the magnetic horns as shown in figure 2. Significant proportion of these particles after traversing a very short distance of about 200m through a decay pipe will be decayed into large flux of muon neutrinos continuing in the same direction [Figure 2].

Fermilab's major injector accelerator will be used as the proton source to produce world's highest intense neutrino beam i.e largest neutrino flux rate for LBNE. Initially LBNE will be started with the current strength of

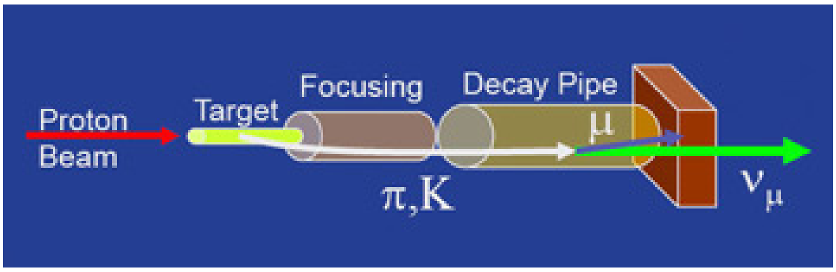

Figure 2: Credit: Fermilab

proton source and undergo an upgradation through Project X which in turn enhance the strength of it by creating more protons [15][16][17].

4.4 LArTPC Neutrino Detector

An advanced Liquid Argon Time Projection Chamber is planned to be used as LBNE far detector. LArTPCs are highly suitable for the study of neutrinos. The pioneering work is being done by the ICARUS collaboration at Gran Sasso National Laboratory,Italy with the largest existing LArTPC detector containing of 600 tons of liquid Argon to detect the neutrinos coming through 730 km rocks from CERN Lab. According to the conceptual design of LBNE(2012), a 10,000 tons of detector will be placed in an evacuated pit near the surface but under the hills with a 3 m covering to shield the cosmic background in the first phase of the experiment. In the later phase, it is hoped to build an even lager detector ($\sim$ 35,000 tons) which will be placed about 4850 level deep underground in Homestake mine[18].

4.4.1 About LArTPC

LArTPC consists of a argon filled cylindrical chamber with multi-wire proportional chambers (MWPC) as end wireplanes. The wireplanes act as an electrostatic grid. Electrons created through ionization are drifted towards this biasing planes. Drifting of ionized electrons also depend on the geometry and fields around each plane. To increase the resolution the wires or plane pitch can be optimized but keeping the sensitivity high. Basic working function of a TPC is listed below [18][20].

- Due to the interaction of incoming high energy particles with the detecting material (argon) placed in the chamber, ionized electrons are being created.

- These ionized electrons are then drifted towards the read-out planes for signal detection.

- Location of the wires in a particular plane give the position information about the interaction while knowledge of drift velocity and T_0(interaction time) used to project back the particles in the drift direction towards the origin.

- Scintillating light produced by the interaction also be collected by photo multiplier tubes and used as triggering to suppress unwanted r adiation.

Typical schematic of LArTPC will be used for Microboone experiment at Fermilab for neutrino detection holds about 100 tons of argon cooled to minus 187 degrees celcius. This experiment consists of a 2.6mx2.5mx12.0m TPC placed in a cryostat as depicted in Figure 3. The projecction chamber will be instrumented with 3 wireplanes having 3mm wire pitch each and about 10,000 electronic readout.

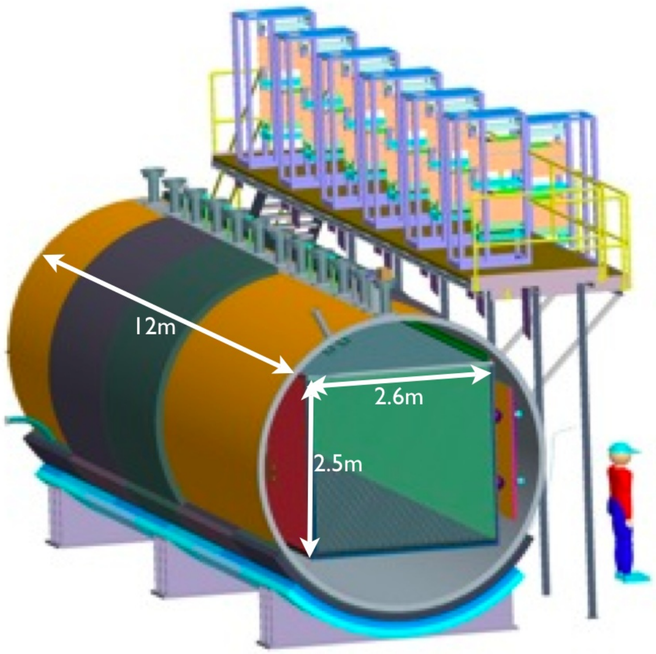

Figure 3: Ref.[20]

4.4.2 Advantages of using Argon

- Both ionization and scintillation produced in the target material can be used for detection.
- Argon being a noble liquid allows the drifted electron to travel a long distance (-meters) through it.
- Due to high dielectric properties argon can accommodate high voltages.
- Above all Argon is relatively cheap and easily available in atmosphere.

5 Simulation Methods

GLoBES - a flexible neutrino oscillation software, is being designed to simulate the Long baseline and Reactor experiments for precision measurement of the neutrino mixing parameters as well as to resolve the CP violation δ_{CP} and mass ordering of neutrinos. In the defined experiment in abstract level, an artificial beam is sent to a detector to measure the outcomes. The measured solutions are needed to analyse the correlations, degeneracies in combination with other experiments. GLoBES is a perfect tool for all these with some more advanced features. It allows the experiment simulation with only one point-like source (like beam and reactor experiments). Geometrical distribution of sources(sun or atmosphere) along with time dependent sources (Supernovae) can not be studied using GLoBES[3][4]. In the following section we introduce the general description that GLoBES use to calculate event rate vectors.

5.1 Event Rates Computation and Integrated Luminosity

GLoBES simulates a neutrino beam travelling from source to detector where neutrino interactions are detected with appropriate instrumentation. The simulator calculates the oscillation probabilities, event rates for the channels that are set for observation in the experiment[18][3][4].

The total event rate is roughly proportional to the product of fiducial detector mass, experiment running time and beam power i.e

$$\mathcal{L} \sim \text{Detector Mass} \times \text{Running Time} \times \text{source Power}$$

Source power can also be represented as useful parent decays (POT(proton on target) collision per year) in case for superbeam experiments. The quantity $\mathcal{L}$ is called Integrated Luminosity which measures the expected performance of an experiment through the average event rate numbers.

GLoBES calculates the event rate vectors by implementing the experiment definition described in the so called glb files which are written in AEDL (Advanced Experiment Definition Language) with an informative description of diferent channel definition appropriate for the proposed experiment. The differential event rates per GeV are computed with

$$n = x \times E \times f \times \text{@norm} \times \text{@power} \times \text{@stored\_muons} \times \text{@time} \times \text{@target\_mass} \times \text{@baseline}^{-2}$$

Here, @ marked parameters are in AEDL syntax described in the glb files. x $\equiv \sigma/E$, E, f are differential cross-section against energy, neutrino energy and flux of neutrino beam respectively. @norm is the overall normalization factor needed to match the units of these elements defined in glb files[18].

6 Data Analysis

6.1 3-Flavor Oscillation Probabilities

It is seen that most of the neutrino oscillation experiments are approximated to follow the 2-flavor oscillation physics. But for an experiment sensitive to 3-flavor effects, designed to observe the exact phenomena much more precisely, this consideration will no longer be true. In case of 3-flavor physics the existance of two oscillation lengths, $4\pi E/\Delta m^2_{21}$ and $4\pi E/\Delta m^2_{31}$ have to be taken into account in the same channel. The sensitivity measurement of different mixing parameters is being calculated either looking at the $\nu_\mu/\bar{\nu_\mu}$ disappearance channel or $\nu_e/\bar{\nu}_e$ appearance channel[19].

Survival Probability of ν_μ Beam

The initial muon neutrinos can oscillate into other neutrino flavors with a survival probability approximated as

P$(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2(1.267\Delta m^2 L/E_\nu)$
Where, L (km) is the baseline length (along which the beam propagates), E_ν (GeV) is neutrino energy and Δm^2 (eV^2/c^4) is the relevant mass squared

splitting[19].

$$\Delta m^2_{32} = m^2_3 - m^2_2 \text{ (Normal Hierarchy)}$$
$$\Delta m^2_{13} = m^2_1 - m^2_3 \text{ (Inverted Hierarchy)}$$

The peak energy of the primary ν_μ beam with 1300 km long baseline length is, $E_\nu = (2 \times 1.267 \times \Delta m^2 L)/\pi = (2 \times 1.267 \times 2.4 \times 10^{-3} \times 1300)/3.14 \simeq 2.518$ GeV, which corresponds to first minimum of ν_μ survival probability.

In the following simulation the transition probabilities of primary ν_μ beam is shown (Figure 4) for both $(\nu_\mu \to \nu_\mu)$ and $(\nu_\mu \to \nu_e)$ channels at $\delta_{CP} = \pi/2$. For, illustration, the values of standard oscillation parameters used in GLoBES to calculate the probabilities are listed below.

- $sin^2\theta_{12} = 0.3$
- $sin^2 2\theta_{13} = 0.1$
- $sin^2\theta_{23} = 0.5$
- $\Delta m^2_{21} = 7.5 \times 10^{-5}\text{eV}^2$
- $\Delta m^2_{31}(\text{NH}) = 2.4 \times 10^{-3}\text{eV}^2$

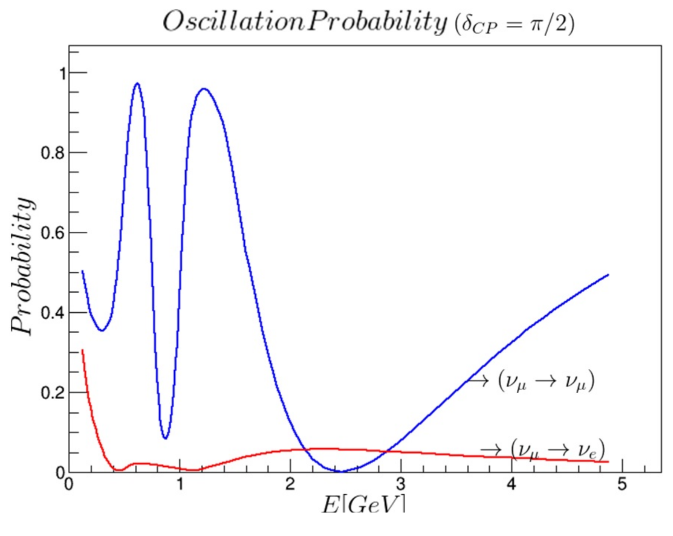

Figure 4: Oscillation probabilities for both $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ channel is shown for $\delta_{CP} = \pi/2$

The dependence of oscillation probability on neutrino energy is plotted (Figure 4) for both $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ channel for a fixed LBNE baseline of 1300km to predict about the oscillation lengths, position of oscillation maxima and minima.

CP Violation in $\nu_\mu \rightarrow \nu_e$ Channel

With the discovery of non-zero θ_{13}, though there is a great possibility to explore the CP violation phenomena in leptonic sector, but due to experimental constraint it is still unknown. Let us examine the CP violation effect in neutrino oscillation probability for 1300 km LBNE baseline with an intial ν_μ beam. The transition probabilities in $\nu_\mu \rightarrow \nu_e$ channel for 3 different values of δ_{CP} is plotted below (Figure 5) with the same parameter specifications stated above[19].

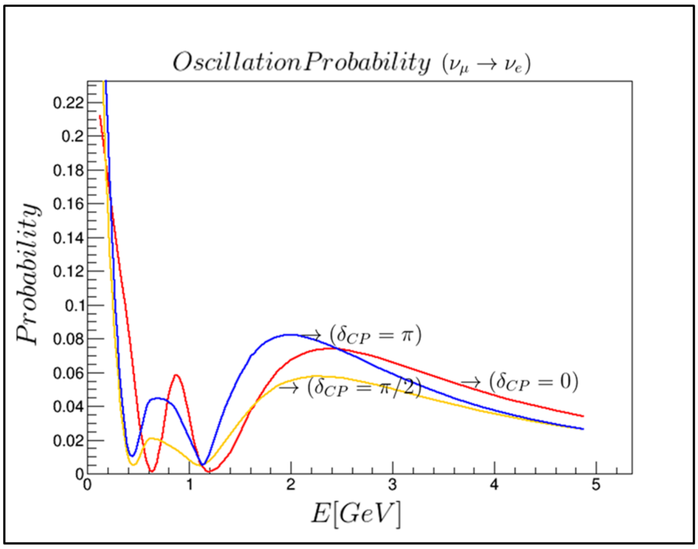

Figure 5: Transition probabilities are plotted for different δ_{CP} values to analyze the CP violation effect in $\nu_\mu \rightarrow \nu_e$ channel

As we can see from figure 5 that oscillation probabilities are strongly depend on the CP violation phase (δ_{CP}). Also the precision measurements of different mixing parameters are evaluated by incorporating the transition probabilities. So, for better accuracy in the sensitivity measurement, the dependence of oscillation probabilities on δ_{CP}, has to be taken into consideration.

6.2 Precision Measurement of θ_{13} and δ_{CP}

In order to understand 3-flavor oscillation effects, LBNE is aimed to measure precisely all the mixing parameters, specially the unknown δ_{CP} in the light of non-zero θ_{13}. To identify the capability of LBNE to measure the unknown δ_{CP}, a simulation has been performed to obtain the confidence regions of finding δ_{CP} constrained by the mixing angle θ_{13}. The sensitivity is demonstrated by computing the χ^2 distribution for different θ_{13} and δ_{CP} values (Figure 6). The minimization is procced by keeping all the parameter fixed except θ_{13} and solar mixing parameters (θ_{23} and Δm^2_{31}). The solar mixing parameters can be fixed without introducing much error and in that case the computation will be much more faster[18].

The resulting $\Delta\chi^2 = \chi^2 - \chi^2_{min}$, is a measure of the confidence level in $\theta_{13} - \delta_{CP}$ plane.

For 5 years of experiment running in neutrino mode, we can see from

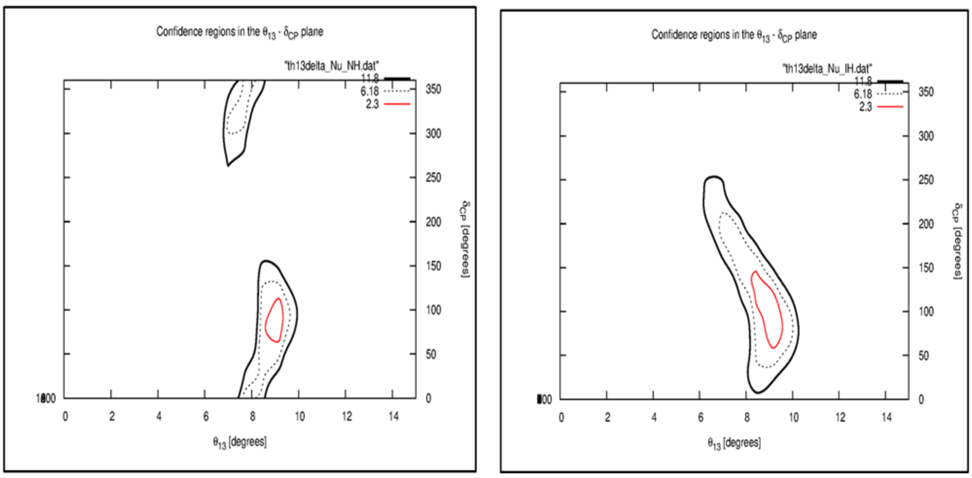

Figure 6: Confidence regions (1σ(Red), 2σ(Dotted), 3σ(Solid Black)) in θ_{13} - δ_{CP} plane has been plotted for both normal (left figure) and inverted (right figure) hierarchy. For simplicity, the octant degeneracy is removed by considering the maximal mixing ($\theta_{23} = 45°$).

the left figure [6] that there is a strong correlation between θ_{13} and δ_{CP} which makes it difficult to efficiently constrain the δ_{CP} value. One way to improve this sensitivity is to run the experiment for several years again but in anti-neutrino mode (Right Figure [6]) as the the dependency of oscillation probabilities on δ_{CP} is different for anti-neutrino than the neutrino.

A betterment of confidence regions in $\theta_{13} - \delta_{CP}$ plane for LBNE comparable with NOva experiment is analysed in the following section (Figure 7). As we can see that the significance contours in θ_{13} - δ_{CP} plane are much smaller at certain confidence levels (1σ, 2σ) for LBNE than NOvA experiment indicating a higher accuracy in sensitivity measurement.

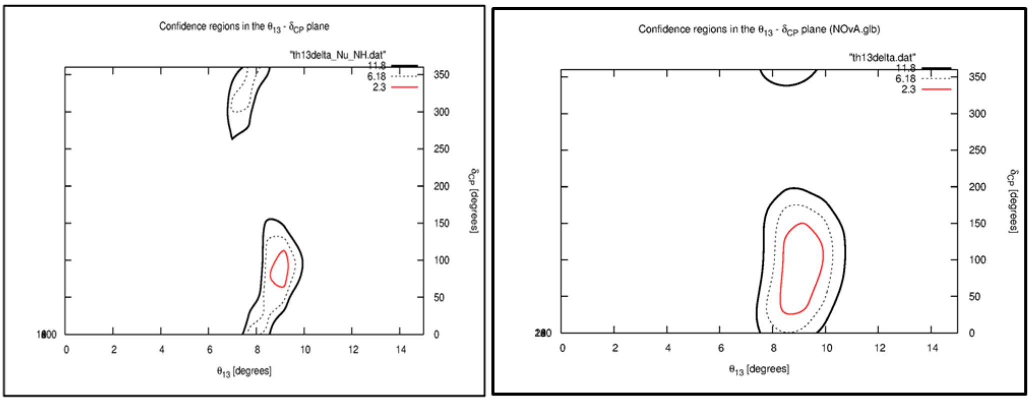

Figure 7: Confidence regions (1σ(Red), 2σ(Dotted), 3σ(Solid Black)) in θ_{13} - δ_{CP} plane has been plotted for both LBNE (Left Figure: 700kW, 5 years ν running mode, 35kt detector mass, 1300 km long baseline) and NOvA (Right Figure: 700kW, 5 years ν running mode, 25kt detector mass, 812 km long baseline) considering normal hierarchy. For simplicity, the octant degeneracy is removed by considering the maximal mixing ($\theta_{23} = 45°$)

6.3 CPV Sensitivity

One of the key research of neutrino experiments is being the possible determination of CP violation leptonic phase δ_{CP}. Given a relatively large mixing angle θ_{13} as recorded from Daya Bay and other reactor experiments, a realistic goal of measuring CP violation exists for next generation long baseline experiments. Here, a study is being done to testify the experiment's ability to search the signs of CP violation. The computation has been performed by comparing the event rates for two sets of data follows from the two CP conserving solutions $\delta_{CP} = 0,\ \pi$ i.e a preliminary consideration of δ_{CP} neither to be 0 nor π would be sufficient for the first phase of CPV observation. The CPV Sensitivity is defined as $\sqrt{\Delta\chi^2}$,which signifies the chance at which CP conserving solutions can be dismissed[18][22]. $\Delta\chi^2$ for this case is defined as

$$\Delta\chi^2_{CPV} = \min(\Delta\chi^2_{CP}(\delta^{test}_{CP} = 0) - \Delta\chi^2_{CP}(\delta^{test}_{CP} = \pi))$$

$$\text{where, } \Delta\chi^2_{CP} = (\chi^2_{\delta^{test}_{CP}} - \chi^2_{\delta^{true}_{CP}})$$

Analysis has been carried out to evaluate CPV sensitivity reach of LBNE for both normal and inverted hierarchy for the following exposure scenarios. $\Delta\chi^2$ is computed by taking into account the systematics and parameter correlations. The minimization process is executed with every parameter except δ_{CP}. Also mass squared difference Δm^2_{31} is kept fixed at its best fit values for both normal and inverted case to account the mass hierarchy.

- 700kW-3+3-10kt
- 1.1MW-3+3-10kt
- 1.1MW-3+3-35kt
- 2.3MW-3+3-35kt

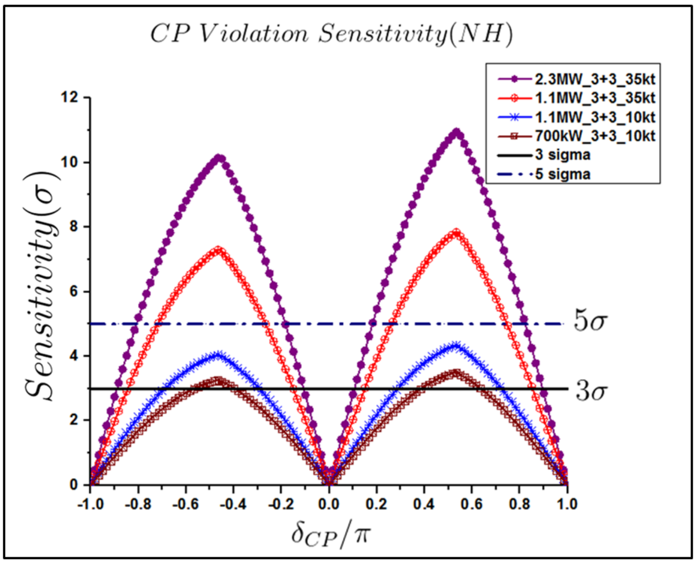

Figure 8: The confidence level at which CP violation ($\delta_{CP} \neq 0,\ \pi$) can be determined for Normal Hierarchy with the above mentioned exposures

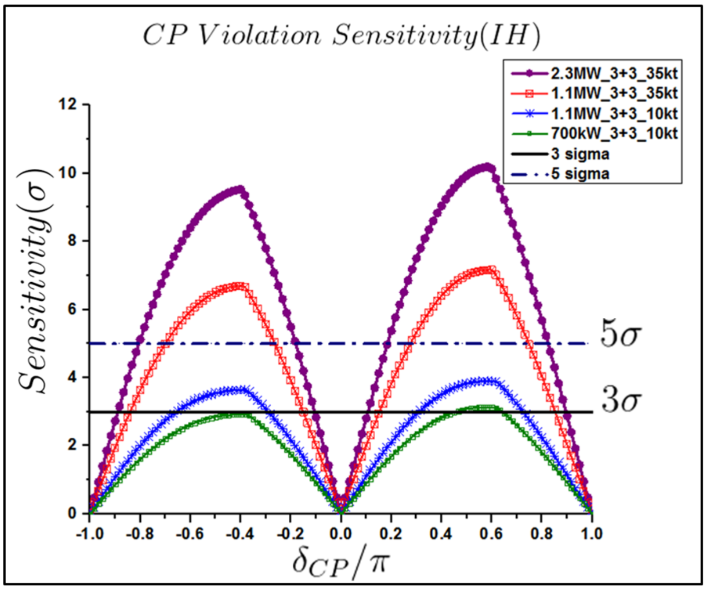

Figure 9: The confidence level at which CP violation ($\delta_{CP} \neq 0,\ \pi$) can be determined for Inverted Hierarchy with the above mentioned exposures

As the true value of δ_{CP} is not known, a complete scan over δ_{CP} ($-\pi$ to $+\pi$) is being performed. The results predict the different confidence levels in evaluating the CP violation for 3+3 equal ν and $\bar{\nu}$ mode of LBNE with varying beam power and fiducial detector mass. It is evident from the results that for 10kt LArTPC detector mass, the sensitivity of determining δ_{CP} for both the mass ordering, does not exceed 5σ confidence level for average beam power 700 kW and 1.1MW. To conclude about the CPV existence, a full scope of 35kt detector mass is needed to be exposed to a high intensity beam power ($\geq$ 1.1MW).

6.4 MH Sensitivity

Considering the 3-flavor oscillation physics, it is possible to resolve the neutrino mass hierarchy at LBNE. Using GLoBES, we can determine the chance to rule out the wrong hierarchy solution by searching the sign of $\Delta m_{31}^2 = m_3^2 - m_1^2$. The mass hierarchy test is performed by calculating the event rates for different values of δ_{CP} and comparing the results for normal and inverted hierarchy case. If the computed $\Delta\chi^2$ values are large enough for the simulated experiment, the tested hierarchy can be ruled out at a certain confidence. The test method computes the event rates for both test values and true values which are assigned with different hierarchies keeping Δm_{31}^2 fixed[18][22]. Therefore, $\Delta\chi^2$ for mass hierarchy sensitivity is defined as,

$$\Delta\chi^2_{MH} = |\chi^2_{MH^{test}=IH} - \chi^2_{MH^{true}=IH}|$$

χ^2 values are calculated for both data sets of test values which are assigned with different hierarchies. The hierarchy inversion can be done by assigning $\Delta m_{31}^2 = -\Delta m_{31}^2 + \Delta m_{31}^2$ for the test values for a true fixed value of Δm_{31}^2, which in turn being set at the begining of the simulation[18][22].

For the following computation, the true values are assigned with normal hierarchy and test hierarchy is choosen as inverted hierarchy against normal hierarchy i.e $\Delta\chi^2 = \chi^2(IH) - \chi^2(NH)$. The resulting $\sqrt{\Delta\chi^2}$ gives us the confidence at which the tested hierarchy can be ruled out for the following case. The computation is considered for standard LBNE attributes with the following exposures:

- 700kW-3+3-10kt
- 1.1MW-3+3-10kt
- 1.1MW-3+3-35kt
- 2.3MW-3+3-35kt

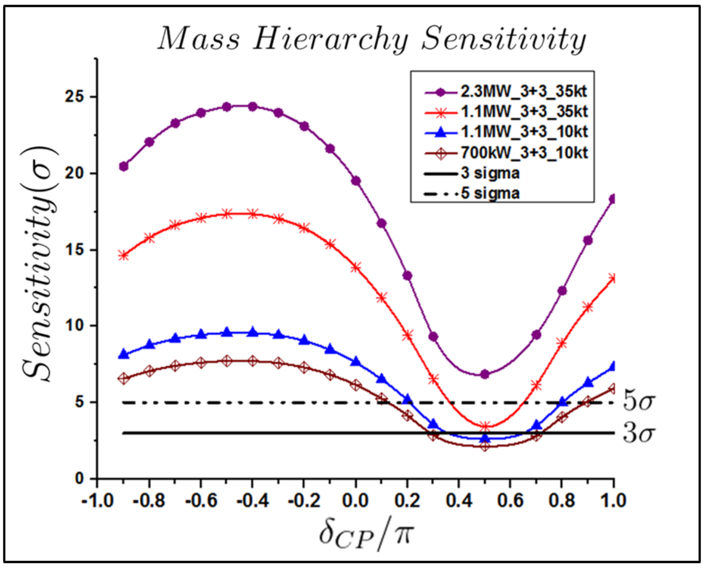

Figure 10: The significance with which the mass hierarchy can be evaluated w.r.t δ_{CP} is shown for the above mentioned exposures where, the true hierarchy is assumed to be the normal one

As, we can see that even for 700kW and 1.1MW beam power for 10kt LArTPC detector, it is not quite possible to rule out the existence of hierarchy degeneracy for complete range of δ_{CP} values. For the significance with which the wrong hierarchy can be rejected at a confidence greater than 3σ for the entire δ_{CP} region, the beam intensity must exceed 1.1MW with the full scope of detector mass (35kt). According to the Project X programme, LBNE with 2.3MW beam power and 35kt detector mass, can prove the true hierarchy at 5σ confidence level completely. From the figure 10, we can say that the MH sensitivity is strongly depend on δ_{CP} values, so for a particular data set if our sensitivity measurement crosses the 5σ confidence level for $\delta_{CP} \approx -\pi$ to 0 , we can conclude about the mass hierarchy to be the normal one otherwise it will be the inverted hierarchy case.

6.5 Conclusions

In this work, a focussed study on the different prospects of identifying the neutrino mixing parameters with a possibility to resolve the intrinsic degeneracies at Long Baseline Neutrino Experiment, is analysed. A primary attention has been paid to explore the possibility of δ_{CP} existence to prove the CP violation in lepton sector also one of the unknown mystery regarding neutrino masses, the mass hierarchy. The whole study is concentrated to estimate the desired performance of LBNE with a LArTPC far detector placed at 4850 level in the Homestake mine. The anaysis performed for LBNE using GLoBES, is being summerized with a successful future note of accomplishing almost all the unrevealed physics in neutrino sector at its full phase.

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