The LBNE near detector

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Abstract. The Long-Baseline Neutrino Experiment (LBNE) is a next generation neutrino oscillation experiment currently proposed for construction in the United States with the main goal of studying muon (anti)neutrinos oscillations into electron (anti)neutrinos over a distance greater than 1000 km and over a wide range of neutrino energies. Its main physics results will be the precision measurement of $\delta_{CP}$ and all three mixing angles. A value of $\delta_{CP}$ different from 0 or $\pi$ will appear in the LBNE data as a small (0% to 40%) asymmetry on the oscillation probability of neutrinos versus antineutrinos. Such a small effect requires a very good control of the systematic uncertainties affecting the measurement and this can only been accomplished using a near detector. I will describe the LBNE near detector complex focusing primarily on its reference design, which includes a set of muon detectors to monitor the beam and a magnetized liquid argon TPC surrounded by a muon identifier detector to measure neutrino interactions at the near site.

1. Introduction
The recent results by atmospheric[1], solar[2], and reactor[3] neutrino experiments established that neutrinos oscillate, that is neutrinos produced in a given flavor state have a non zero probability of being detected in a different flavor state. The only consistent explanation of all the data collected so far is that neutrino are not massless, and that mass eigenstates (i.e. eigenstates of the free Hamiltonian) are different from weak eigenstates (i.e. eigenstates of the full Hamiltonian, including the interaction terms).

The oscillation probability in vacuum depends on the energy $E$ of neutrinos, on the distance $L$ between the source and the detector, on the differences between the neutrino mass eigenvalues $\Delta m^2_{ij}$ and on the elements of the so called neutrino mixing matrix $U$, relating neutrino mass eigenstates $\nu_i$ with neutrino flavor eigenstates $\nu_\alpha$.

In the case of $n$ neutrino flavors and $n$ massive neutrinos the unitary $n \times n$ matrix $U$:

$$\nu_\alpha = U_{\alpha,i} \nu_i \quad \alpha = e, \mu, \tau, ..., n \quad i = 1, 2, 3, ..., n$$ (1)

can be parametrised by $n(n - 1)/2$ Euler angles and $n(n + 1)/2$ phases [4].

The measurement of the decay width of the $Z^0$ boson into neutrinos proves that the number of light ($m_\nu \leq m_Z/2$) active neutrinos is exactly three, therefore a fourth neutrino must not couple to the standard electroweak currents, that is, it must be sterile.

At present almost all neutrino data are consistent with the assumption that there are only three neutrino mass eigenstates and three flavor eigenstates, and therefore in this paper I shall consider the "standard" scenario where the three light active neutrino flavor states ($\nu_e, \nu_\mu, \nu_\tau$) and the three known mass eigenstates ($\nu_1, \nu_2, \nu_3$) participate in the oscillations. Then, $U$ is
a 3 × 3 matrix analogous to the CKM matrix for the quarks, and it can be parametrized by three mixing angles \( \theta_{12}, \theta_{13}, \theta_{23} \) and three complex phases (\( \delta_{CP}, \eta_1, \eta_2 \), two of which (\( \eta_1, \eta_2 \)) are physical only if neutrinos are Majorana fermions [5] and do not affect neutrino oscillations [6] [7].

In order to relate the elements of the mixing matrix to experimental observables, one needs to order the neutrino mass eigenvalues. This is done by requiring that: \( m_2^2 > m_1^2 \) and \( \Delta m_{21}^2 < |\Delta m_{31}^2| \). In this case, there are three mass related oscillation observables: \( \Delta m_{21}^2 \), \( |\Delta m_{31}^2| \), and the sign of \( \Delta m_{31}^2 \). A positive (negative) sign for \( \Delta m_{31}^2 \) implies \( m_1^2 > m_2^2 > m_3^2 \) (\( m_3^2 < m_2^2 \)) and characterizes the so-called normal (inverted) neutrino mass hierarchy.

Our current knowledge of neutrino oscillation parameters is summarized by [8] [9] [10]:

\[
\begin{align*}
\Delta m_{21}^2 &= 7.59^{+0.20}_{-0.18} \times 10^{-5} \text{eV}^2, \\
\Delta m_{31}^2 &= 2.50^{+0.08}_{-0.09} \times 10^{-3} \text{eV}^2 \\
\sin^2 \theta_{12} &= 0.312^{+0.017}_{-0.015}, \\
\sin^2 \theta_{23} &= 0.52 \pm 0.06, \\
\sin^2 \theta_{13} &= 0.092 \pm 0.017
\end{align*}
\]

There is no information, at present, about the value of \( \delta_{CP} \) and on the sign of \( \Delta m_{31}^2 \). The measurement of \( \delta_{CP} \) and the determination of the correct ordering of neutrino masses are two main goals of the Long-Baseline Neutrino Experiment (LBNE), a next generation neutrino oscillation experiment to be constructed in the United States.

In its reference design LBNE will consist of three main facilities; a new high intensity neutrino beam at the Fermi National Accelerator Laboratory (Fermilab) aimed at the Sanford Underground Laboratory at Homestake (Sanford Laboratory), 1300 km away, where a massive neutrino detector will be built and, a near detector complex located at Fermilab downstream of the target. With a baseline \( L \) of 1300 km and a neutrino beam energy peaking between 1 and 6 GeV LBNE will achieve an unprecedented sensitivity for the determination of \( \delta_{CP} \) and of the mass hierarchy.

The oscillation channel investigated by LBNE will be the \( \nu_\mu \to \nu_e \) appearance and its antineutrino counterpart \( \bar{\nu}_\mu \to \bar{\nu}_e \) and the measurement will rely on the MSW effect [11].

In the hypothesis that the density of the matter along the path of neutrinos is constant, a reasonable hypothesis for the baseline in question, the oscillation of \( \nu_\mu \) in matter in a 3 × 3 mixing scenario is approximately given by [12]:

\[
P(\nu_\mu \to \nu_e) \approx \sin^2 \theta_{23} \sin^2 \theta_{13} \frac{2\theta_{13}}{(A - 1)^2} \sin^2((\hat{A} - 1)\Delta) + \\
\pm \alpha^2 \sin \delta_{CP} \cos \theta_{13} \sin \theta_{12} \sin \theta_{13} \sin \theta_{23} \sin(\Delta) \sin((1 - \hat{A})\Delta) \\
\pm \alpha \cos \delta_{CP} \cos \theta_{13} \sin \theta_{12} \sin \theta_{13} \sin \theta_{23} \cos(\Delta) \sin((1 - \hat{A})\Delta) \\
+ \frac{\alpha^2 \cos^2 \theta_{23} \sin^2 \theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)
\]

where \( \alpha = \Delta m_{31}^2 / \Delta m_{21}^2 \), \( \Delta = \Delta m_{31}^2 L/4E \), \( \hat{A} = 2VE/\Delta m_{31}^2 \), \( V = \pm \sqrt{2}GFn_e \) is the matter potential, \( GF \) is the Fermi coupling constant, \( n_e \) is the density of electrons in the matter. The + sign in the second term of equation 4 and in the matter potential refers to neutrinos, the – sign to antineutrinos. The second and third terms in equation 4 control the sensitivity to CP violation through the parameter \( \delta_{CP} \), and the first three terms predict a matter induced enhancement for the normal mass ordering (\( \Delta m_{21}^2 > 0 \)) and a suppression for the reversed mass ordering (\( \Delta m_{31}^2 < 0 \)) through \( \alpha, \Delta \) and \( \hat{A} \). At a baseline of 1300 km the oscillation probability will be in the 5-10% range at the first oscillation maximum between 2 - 3 GeV, and at lower energies both the size of the probability and the effect of the CP phase will be larger.
2. Motivation for a Near Detector complex

LBNE will study neutrino oscillations by measuring event rates at the far detector (FD) with high statistics. In order to extract the oscillation probabilities from the measurement above it is paramount to precisely predict such rates, and therefore to gain a detailed enough knowledge of both the signal and backgrounds.

In the energy range where the first and second oscillation maxima are expected at the LBNE FD the neutrino cross sections and the momenta of the outgoing particles are poorly known (pion production in the resonance regime is an example), and it is therefore crucial to measure the neutrino fluxes and interaction channels at a near site, before the fluxes have been affected significantly by neutrino oscillations. This task will be performed by the LBNE near detector complex, a suite of detectors with the purpose of making all those measurements required to mitigate the effect of the large systematic uncertainties affecting neutrino fluxes, cross sections and background in the region of interest in such a way that the ultimate sensitivity of LBNE is not limited by them.

Given the energy range where the $\nu_\mu \rightarrow \nu_e$ oscillation probability peaks, it is necessary, in particular, to focus on $E_\nu < 8$ GeV, as well as on higher neutrino energies that produce background in the region of interest for the oscillation signal. In this region it is critical to identify and measure processes that can mimic oscillation signals at the far detector; among these the intrinsic $\nu_e$ (and in its antineutrino counterpart when running the accelerator in antineutrino mode) background in the beam is of particular interest when investigating the $\nu_\mu \rightarrow \nu_e$ oscillation channel, and it has to be known with sufficient precision to be subtracted at the far site.

$\nu_e$ (and $\bar{\nu}_e$) are detected through their charged current (CC) interactions, and in particular through the measurement of the outgoing charged electron (anti-electron).

Another dangerous background for these interactions is represented by neutral current (NC) events containing $\pi^0$s, the dominant source of background from neutrino NC interactions. $\pi^0$s decay to two gammas which, after conversion to $e^+e^-$ pairs, initiate an electromagnetic shower that can be difficult to distinguish from an electron shower.

It is paramount to be able to separate muons from electrons in order to distinguish $\mu$ and $e$ CC interactions.

The other important ingredient necessary to predict the event rates at the FD is the knowledge of the neutrino flux; since the hadron production models used to simulate hadron propagation and interaction in the target and horn materials are not well constrained, measurements of particles in the decay region as well as external measurements of hadron production and propagation in the target and horn materials are highly desirable.

3. The near detector complex

In what follows I shall describe the reference design for the near detector complex as described in the Conceptual Design Report document, phase 1; LBNE is currently undergoing a process of revision and the complex described here might not be the actual one.

The near detector complex will be located at Fermilab, downstream of the beamline, and will consist in a set of beam line measurements (BLM) and a neutrino detection (ND) system.

The ND will be placed underground in the Near Detector Hall 450 m downstream of the target, with the purpose of measuring or constraining neutrino fluxes and spectra and to measure the neutrino-interaction channels important for predicting the signal and backgrounds at the far site.

The BLM will be placed in the region of the absorber at the downstream end of the decay region. Its goal is to determine the neutrino fluxes and spectra and to monitor the beam profile on a spill-by-spill basis, and this will be achieved by measuring the muons exiting the decay volume. In fact, the two-body decays of pions and kaons that produce neutrinos also result
in the creation of a daughter muon. Since muons and neutrinos come from the same parent pion and kaon decays, a measurement of the absolute muon flux in conjunction with the energy spectrum seen in the muon monitors can confirm the absolute neutrino flux.

LBNE will also rely on a set of external (performed, for example, using the MIPP or NA61 detectors) hadron-production measurements, some of which will be performed as a part of the project itself. The simulation of the hadronic cascades in the target, horn and decay tunnel require an accurate knowledge of the phase-space distribution of the initial proton beam, of the geometry and material of all the elements in the beamline, of the hadron-production cross sections and of the meson-to-neutrino decay rates. All these items can be simulated accurately except for the hadronic cascades, whose prediction relies on models based on hadron-production measurements. In order to keep the uncertainty in the near/far event-rate ratio from being limited by systematic uncertainties in the flux, the LBNE flux simulation must be accurate at the 4-5% level.

3.1. Muon Measurement Facilities

Figure 1 shows a conceptual layout of the muon measurement systems.

Figure 1.

The first set of muon-measurement devices, from left to right, is the ion-chamber array which is mounted directly to the rear wall of the absorber. Following that, a set of three variable-pressure gas Cherenkov counters, and finally a set of stopped-muon counters which are interspersed between walls of steel blocks. The blocks are there to provide several depths at which to monitor the stopped muons as they range out in the material.

The ion-chamber array has the purpose of monitoring the stability of the beam direction over time; even a tiny misalignment of the beam can in fact result in a significant change of the flux at the FD. Because the muon monitors will be located approximately 275 m from the beam target, this requires a measurement of the muons to an accuracy of approximately 5 cm. To keep the change in the neutrino beam less than 1% in all energy bins, the beam direction must be known to a precision of approximately 0.2 mrad.

The muon monitors must also be capable of operating in a high-radiation environment; the rate of muons crossing the monitors will in fact be approximately equal to 50 million muons
per cm$^2$ for a pulse of $10^{14}$ protons-on-target. Due to their high radiation tolerance, sealed ionization counters are the default technology, and the conceptual design is based on commercial ion chambers by LND, Inc. model 50343. The chambers will be mounted in a $5 \times 5$ grid, four meters by four meters and arranged as shown in figure 1.

One disadvantage to ionization counters is that they measure the total ionization deposited from all particle species (including the delta-ray electrons produced by the muons), making it challenging to convert the ionization signal into an absolute muon flux. The LBNE ND complex plans to use the ionization counters to monitor the beam stability, direction and shape, but not to determine the absolute flux of muons or to determine the muon-energy spectrum, for which, respectively, the gas Cherenkov counters and the stopped-muon counters will be used.

The method exploited by the stopped-muon counters is to stop muons in a material with significant carbon content and, via muon capture, to produce $^{12}$B that will in turn undergo $\beta$ decay. The high-carbon material, in this case graphite, surrounds a Cherenkov radiator material which is sensitive to electrons from muon decay or high-energy beta decays. $\mu^+$ will be identified based on their 2.2 $\mu$s decay time. The detectors would only operate in the lower-rate environment that is present many microseconds after the beam pulse is over.

As mentioned above, the muon flux will be measured in the near detector complex using Cherenkov counters. They will be deployed downstream of the absorber and will not image individual Cherenkov rings, but rather see the integrated signal from many muons due to the very large instantaneous flux. In addition, by varying the radiator gas pressure, and hence the Cherenkov threshold, the systems index of refraction would vary, allowing it to map out the muon momentum distribution. The conceptual design is based on a traditional beamline Cherenkov counter, where a gas radiator is contained in a pressurized tube.

### 3.2. Neutrino Detector

The reference design for the LBNE FD is a massive Liquid Argon Time Projection Chamber (LAr-TPC); to avoid including unnecessary uncertainties from extrapolation between different nuclei, the neutrino detector at the near site will include the same nuclear target as the Far detector.

Its reference design is a magnetized LAr-TPC consisting of the following components:

- a cryostat to contain the cryogenic liquid-argon volume
- a time projection chamber (TPC) immersed in the LAr volume
- read-out electronics and data acquisition for the TPC
- a 0.4-T dipole magnet surrounding the cryostat
- a muon-identifier detector (MuID) on the sides and ends of the magnet

The total active mass of the TPC will be 18 t: with a 120-GeV proton beam, assuming $0.5 \times 10^{14}$ protons per beam spill, this corresponds to 3 events per spill in the active volume.

The vertex resolution if the LAr-TPC will be sufficiently good ($< 1$ cm) to determine whether a track comes from the vertex (in the case of an electron) or is displaced from the vertex (in the case of a gamma).

The detector will also allow the reconstruction of the incident neutrino energy for CCQE events with good resolution in order to measure the neutrino fluxes as a function of energy and the reconstruction of neutral and charged pions produced in NC and CC scattering events. This is important because $\pi^0$ events constitute the largest background to $\nu_e$ and $\bar{\nu}_e$ appearance and $\pi^+$ and $\pi^-$ events constitute the largest background to $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance (this last channel is used to make precision measurements of $\theta_{23}$ and $\Delta m^{2}_{32}$).

The presence of a magnetic field within the detection volume is required to measure the momentum and charge-sign of the reaction products from NC, CC and CCQE interactions to
allow the determination of the beam flux at the near site and the measurement of $\nu_e$ appearance backgrounds. In this respect, separating $\mu^+$ and $\mu^-$ is particularly important in antineutrino running, when the contamination of wrong sign neutrinos in the beam is larger. A magnetic field of 0.4 T over the length of the tracker is sufficient to allow for the determination of the charge-sign of the muons. The magnetic field will be generated by a dipole magnet modeled on the large-aperture UA1 magnet.

The MuID will consist of inexpensive scintillator planes interspersed between the thick steel plates of the dipole magnet. This detector is only meant to provide the identification of the muon, the muon momentum will be measured by the TPC inside the magnetic field. The motivation for it is that $\pi$s and $\mu$s have similar energy depositions, and $\pi$s misidentified as $\mu$s could be erroneously included in the CC $\nu_\mu$ spectra.

Besides the reference design presented here a more expensive alternative design based on a Straw Tube Tracked has also been prepared, and the details about both designs can be found in the Conceptual Design Report.

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