Abstract

The Long-Baseline Neutrino Experiment (LBNE) is aimed at determining the degree to which neutrino interactions violate CP symmetry. Violation of CP symmetry in neutrino interactions could account for the observed asymmetry between matter and antimatter in our universe. Specifically, LBNE will make estimates of neutrino CP violation through the study of neutrino flavor oscillation. A muon neutrino beam, generated at Fermi lab, will propagate more than 1000 kilometers underground until it reaches a 200 kT water Cherenkov detector capable of detecting the aforementioned flavor oscillations. Given the nature of the detector, it is useful to run simulations of neutrino interactions with water; this will tell physicists approximately what results to expect at LBNE as well as provide control data with which physicists can evaluate the effectiveness of their data interpretation methods. This summer I set up the neutrino interaction simulation software GENIE and used it to generate probabilities for interactions between different neutrinos and the constituents of water. I also scanned simulated neutrino interaction data with the goal of determining how effectively events of interest can be distinguished from imposter events of interest when interpreting LBNE data.

LBNE GENIE Simulations and Data Scanning

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1) Neutrino Oscillation

The flavor eigenstate of a neutrino governs how that neutrino interacts via the weak nuclear force. “Neutrino oscillation” refers to the phenomenon where a neutrino in one flavor eigenstate changes to a different flavor eigenstate as it propagates though space. Neutrino oscillation is a result of the relationship between neutrino flavor eigenstates and neutrino mass eigenstates. The three neutrino flavor eigenstates are related to the three neutrino mass eigenstates by a unitary transformation. Hence, the flavor of a neutrino is completely determined by its superposition of mass eigenstates. However, mass eigenstates propagate through space at different frequencies, and so as a neutrino travels through space its superposition of mass eigenstates changes, e.g. at a certain point in space eigenstate one may dominate, whereas at different point in space eigenstate two may dominate. Since the flavor eigenstate of a neutrino is completely determined by its superposition of mass eigenstates (via the aforementioned unitary transformation), as a neutrino travels through space its flavor eigenstate also changes. In a simplified, but relevant and important, model with only two neutrino flavors and two mass eigenstates, the probability that a neutrino will oscillate to a different flavor depends on its distance traveled, its energy, the masses of the two mass eigenstates, and the exact nature of the unitary transformation relating the mass and flavor eigenstates. Specifically, the probability of oscillation is $\sin^2(2\theta)*\sin^2(\Delta(m^2)L/4E)$, where $\Delta(m^2)$ is the difference of the squares of the masses of the two mass eigenstates, L is the distance traveled, E is the energy of the neutrino, and θ is the so-called mixing angle, which uniquely determines the unitary transformation relating the mass and flavor eigenstates.

2) LBNE: Neutrino Generation and Propagation

A beam of neutrinos will be generated at Fermi lab using the following procedure. Protons will be accelerated into a durable target producing unstable particles, specifically pions and kaons. These in turn will decay into muons and muon neutrinos. Because neutrinos only interact weakly and gravitationally, some of the muon neutrinos will be able to travel through rock, underground, to the water Cherenkov detector over 1000 kilometers away. The neutrinos can be expected to travel in approximately the same direction as the initial proton beam due to conservation of momentum. It is important to note that the beam starts off with only muon neutrinos. Physicists will be looking for oscillations where muon neutrinos change into electron neutrinos (muon and electron are different neutrino flavors).

3) LBNE: Cherenkov Radiation and Neutrino Detection

Nothing can travel faster than the speed of light in a vacuum. However, the speed of light in a medium, say water, is slower than the aforementioned universal speed limit, c. When a charged particle travels through water faster than light does, light known as Cherenkov radiation is emitted. A charged particle passing through water excites the constituent water molecules. When these water molecules return to a lower energy state a photon is emitted. If the charged particle is moving faster than the speed of light these photons are emitted in phase and interfere constructively. This constructive interference is a classical effect; it is the same effect responsible for the so-called “sonic boom” when an object travels faster than the speed of sound. The way neutrinos will be detected in the Long-Baseline Neutrino Experiment is by their Cherenkov radiation signature (detected by photomultiplier tubes), which is created when the ultra relativistic neutrinos enter the 200 kT detector full of water and interact weakly with the water molecules. These interactions create muons or electrons, depending on the flavor of the neutrinos, which then gives rise to Cherenkov radiation. By examining the Cherenkov radiation signatures physicists should be able to distinguish muons from electrons from other chance events and therefore determine which flavors of neutrinos entered the detector.

4) Scanning: Electrons, Muons and Pions

How do researchers determine the difference between a muon and an electron signature in the water Cherenkov detector? The only difference between a muon and an electron is mass, a muon is much more massive. It is this difference that allows physicists to distinguish the two events. Classically, kinetic energy is transferred most efficiently from a moving object to a stationary target when they are both the same mass. When an electron is created in the detector via a weak interaction, it collides with and transfers kinetic energy to other electrons, which then themselves induce Cherenkov radiation. When a muon is created in the detector via a weak interaction it does not transfer much of its energy to electrons it collides with, since it is much more massive than they are. This is how researchers tell the difference between electron and muon events.

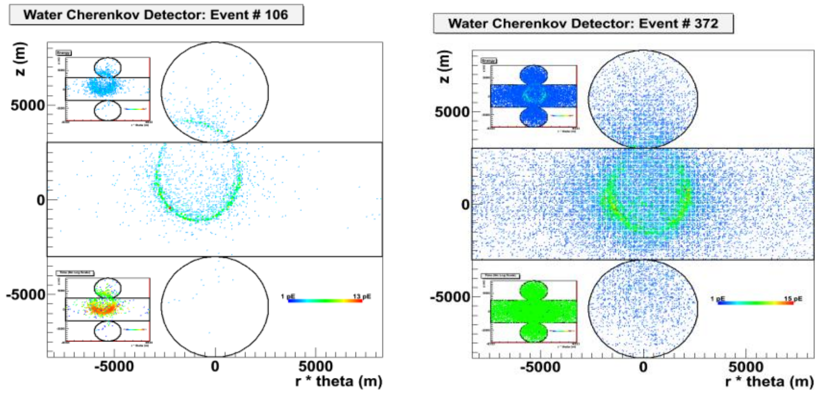

Figure 1: Simulated data: On the left, a probable muon event, characterized by a single clear ring. On the right, a probable electron event, characterized by a single “fuzzy” ring and additional Cherenkov radiation.

What about imposter events? The most common imposter events come from pion production in the detector. Sometimes when a neutrino with enough energy interacts with a hadron, the spins of all three quarks in the hadron get flipped so they are pointing the same way. This is an excited state for the hadron; when it transitions back to its normal state a pion is produced. There are two types of pions that can be produced. One is stable and the other is unstable. The stable pion has a mass similar to the muon and may be confused for a muon when interpreting data from the water Cherenkov detector. The unstable pion quickly decays into two gamma rays, which may be confused for electrons when interpreting data from the water Cherenkov detector. Consequently, physicists need to be confident that they can distinguish these pion events from muon and electron events. It would be disastrous, for example, if an electron neutrino interacting with water to create an electron were indistinguishable from a pion event created by a muon neutrino. It would appear as if a neutrino oscillation had occurred when it fact it had not! This is the reason that I was set to work scanning thousands of simulated neutrino interaction events. Computers were unable to distinguish pion events from electron events to a satisfactory degree, and so humans needed to be used. Humans are better at recognizing visual patterns that computers are. Despite the fact that I scanned a few thousand events, the scanning work is nowhere near complete. There are still many more events to be scanned, and each event needs to be scanned by multiple scanners to mitigate the bias of each individual human scanner.

5) GENIE

GENIE stands for Generates Events for Neutrino Interaction Experiments; it was developed by an international team of neutrino interaction experts. The data I scanned was generated using different software. It is advantageous to run simulations with multiple softwares to avoid biases from a single software. GENIE uses Monte Carlo simulation methods to generate data from simulated interactions between neutrinos and targets given a probability distribution for the different types of interactions. I got GENIE up and running and used it to generate interaction probabilities for different neutrinos interacting with the constituents of water, Hydrogen and Oxygen.

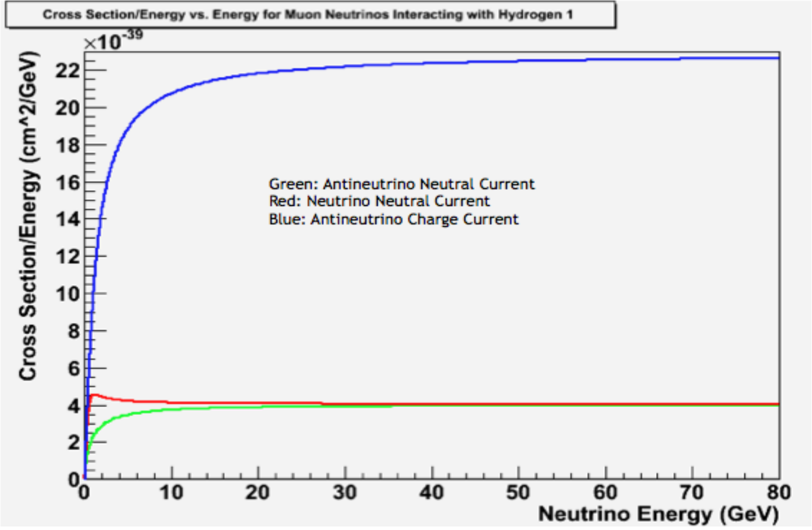

Figure 2: Probabilities for different muon neutrino interactions with Hydrogen.

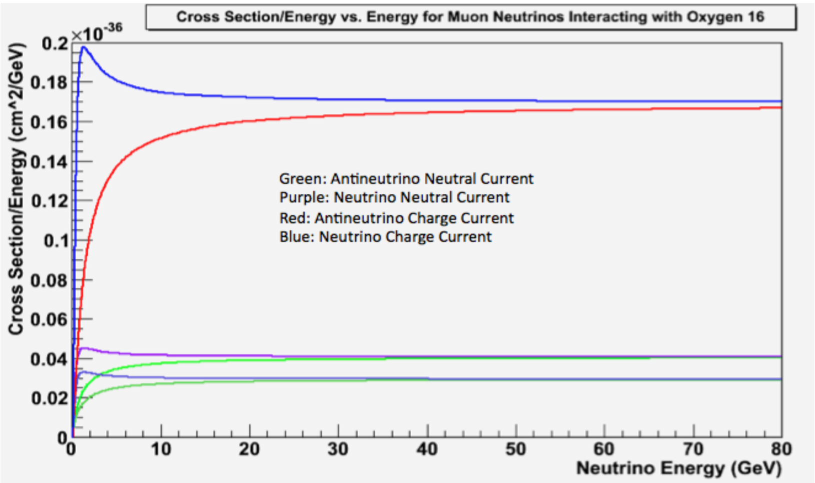

Figure 3: Probabilities for different Muon neutrino interactions with Oxygen. The neutral current interactions each have two lines. The less probable, in both cases, is an interaction where a pion is produced.

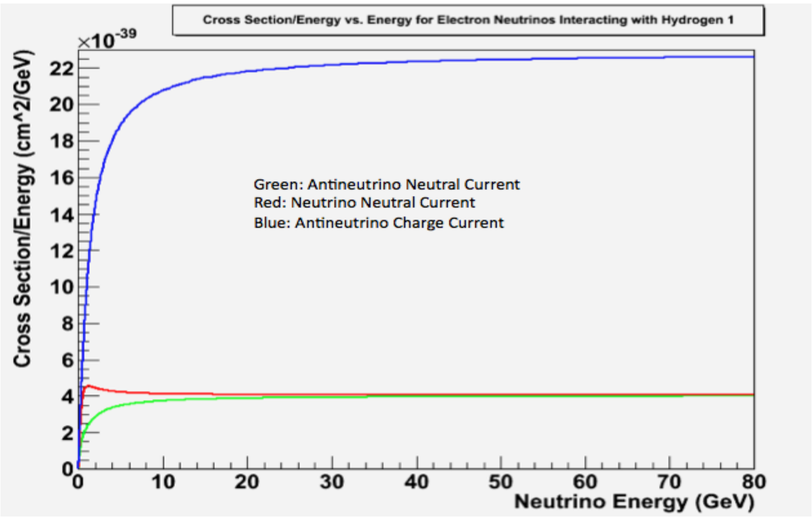

Figure 4: Probabilities for different electron neutrino interactions with Hydrogen.

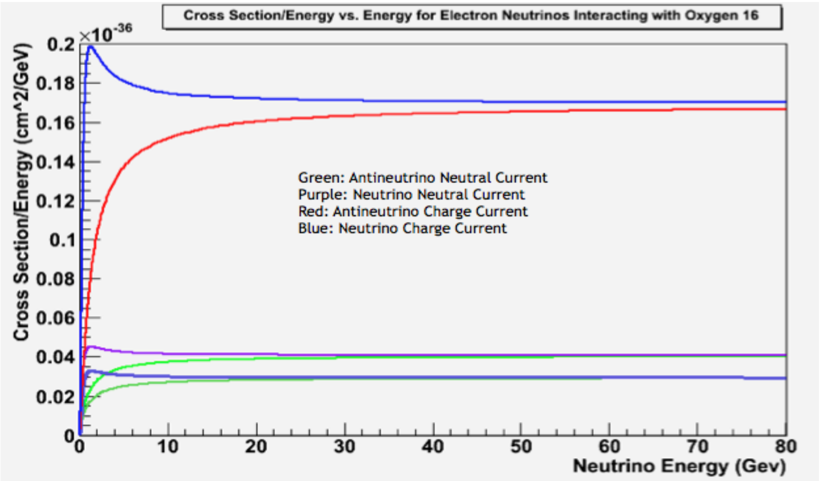

Figure 5: Probabilities for different electron neutrino interactions with Oxygen. The neutral current interactions each have two lines. The less probable, in both cases, is an interaction where a pion is produced.

Once an energy spectrum for the neutrino beam from Fermi lab is available, researchers will be able to use GENIE to simulate interactions between the neutrino beam and the water in the Cherenkov detector. They will also need to simulate interactions between the neutrino beam and the rock between Fermi lab and the detector. This will give a general idea of what results physicists can expect out of LBNE as well as provide data with known physics, which will allow researchers to practice matching visual data to specific physical interactions.

6) Summary

The Long-Baseline Neutrino Experiment is aimed at improving our understanding of the neutrino oscillation phenomenon. Ultimately, it should reveal insight as to the degree to which neutrinos violate CP symmetry. If they do violate CP symmetry significantly, this could explain the observed matter antimatter asymmetry in our universe. My contribution to the project was setting up the GENIE simulation software and scanning simulated data. My work will help researchers determine what results they can expect at LBNE as well as provide an estimate for how well researchers will be able to interpret LBNE data

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