Search of Sterile Neutrino in MicrobooNE

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ABSTRACT

MicrobooNE is a liquid argon Time Projection Chamber(TPC) used for studying neutrino oscillations. It is currently contributing data to the Deep Underground Experiment and it is providing important data to help us find the sterile neutrino, which can help to explain the low energy excess phenomena. After a search for the eV-scale sterile neutrino oscillations in the liquid argon detector, it shows no evidence that the sterile neutrino really exists. The exclusion limits have also been calculated and it comes up with a frequentist CLs exclusion contour with 95% confidence level.

I. INTRODUCTION

Microboone is a liquid argon TPC built at Fermilab to collect the data about neutrinos. A critical function of MicrobooNE is to observe the low energy excess event. In the past, microboone was an important part of the Short baseline experiment. It is now bringing crucial input toward the Deep Underground Neutrino Experiment to build up better neutrino detector. [9]

Neutrino background

In 1930, in order to explain why there is a loss of angular momentum during beta decay, Wolfgang Ernst Pauli suggested the existence of neutrinos. In 1956, Clyde Corwin, Frederick Reines and others first discovered neutrinos. By the standard model, neutrinos are leptons, which have half spin. They can be divided into three flavors: electron neutrinos, muon neutrinos, and tau neutrinos. They are exceptionally hard to detect because they only interact with the gravity and weak force. However, there may be an exception which is the sterile neutrino. In 1967, the sterile neutrino was first proposed by Bruno Pontecorvo. As the sterile neutrino only interacts with gravity, If it exists, it will be even harder to observe. [6]

In 1998, the super-Kamiokande experiment found the first evidence of neutrino oscillations. Which means that neutrinos keep changing their flavor as they propagate through space. The neutrino oscillation happens because each flavor of neutrinos is a specific mixture of mass eigenstates, with different DeBroglie wavelengths, and the waves of mass keep interfering with each other, which make the flavor change. [10] The mass eigenstates of the three flavors of neutrinos are called ν_1, ν_2, and ν_3 respectively, and the masses of them are m_1, m_2, and m_3.

Structure of Microboone Detectors

In liquid argon, under the precise control of the electric field, electrons collide to the wire plane at different angles and all of the ionised electrons are gathered. By a reconstructed algorithm, the 3D trajectory of the neutrino motion can be simulated. [7] The MicrobooNE detector is a rectangular prism with size 2.3m x 2.6m x 10.4m (Figure 1). By applying electric current to a series of 64 2.54 cm diameter stainless steel tubes that form rectangular loops, the electric field is created. The tubes also form a Faraday cage, isolating the electric field from the outside. [7]

Liquid argon provides many benefits as the medium of TPC. When the energy-carrying particles pass by, the liquid argon produces photons, making it easier for detectors to follow the particle's trajectory. At the same time, liquid argon also has an extremely high density, so it has a greater chance of interacting with neutrinos and other extremely low-mass particles. It is also a noble gas, is stable and relatively cheap.[3]

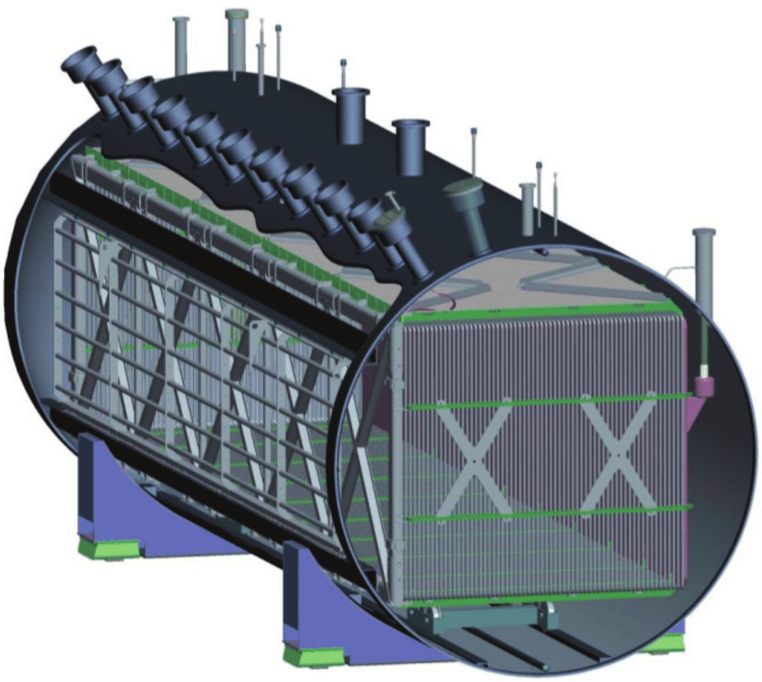

FIG. 1. The prism structure of the Microboone detecter

The Microboone detector is made of several important systems. One of the important components is the light collection system. The wires distributed in the detector can gather wire read-out signals in time which reveal the 3D trajectories of the particles. Those electric signals are important to provide the information about the particle interactions and the absolute time of those events. [4]

Another important component of the Microboone is the UV laser system. The system's main job is to measure the E-field in the TPC. A UV laser system can produce a laser with 266 nm wavelengths by multiphoton ionisation. The UV laser system is composed of two parts and installed at both ends of the Microboone. The laser will ionise electrons along the path of the laser. These electrons will then be released along the real track and their motion will be changed because of the influence of the E-field. The UV laser system will reconstruct the laser's track by using measurements of the displaced electrons. By determining the displacement between the reconstructed location of the UV laser track and the real laser path, the UV laser system can measure the E-field distributed in the TPC precisely. [4]

The Cosmic tagger ray system is also essential in TPC. It is composed of scintillating strips with wavelength shifting fibers paved on the surface of TPC. The scintillating planes are composed of the top, bottom, two sides, and the pipe side planes. When particles pass through, the Cosmic tagger system can measure the time periods when the particles pass and the coordinates of those particles. It will identify and reject muon tracks that come from the cosmic muons, rather than internal neutrino events.[7][4]

How to create a neutrino beam?

To study neutrino properties, the booster neutrino beams are produced at Fermi Laboratory, the neutrino beam is created in the Booster Neutrino Beam-line. Using the cockroft-Walton generator, the protons are first collected from hydrogen gas. They will process in a linear accelerator to receive about 400 MeV Kinetic energy which will create a proton beam. The proton beam will then collide with the beryllium target, and split into pions and kaons. By the electromagnetic field, the charged pions will be focused to form a “pion beam.” [7] [2]While passing a 200m long region, the decay pipe shown in Figure 2, the charged pions will decay into muons and muon neutrinos due to weak interactions: [8] [2]

$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$ and $\pi^{-} \rightarrow \mu^{-} + \nu_{\mu} \bar{\nu}_{\mu}$.

At last, the muons will be blocked by a thick shielding formed by absorber and a layer of dirt and rock. However, the neutrinos will pass the barriers easily. it will form a pure neutrino beam and enter into the detectors for collecting data. [6]

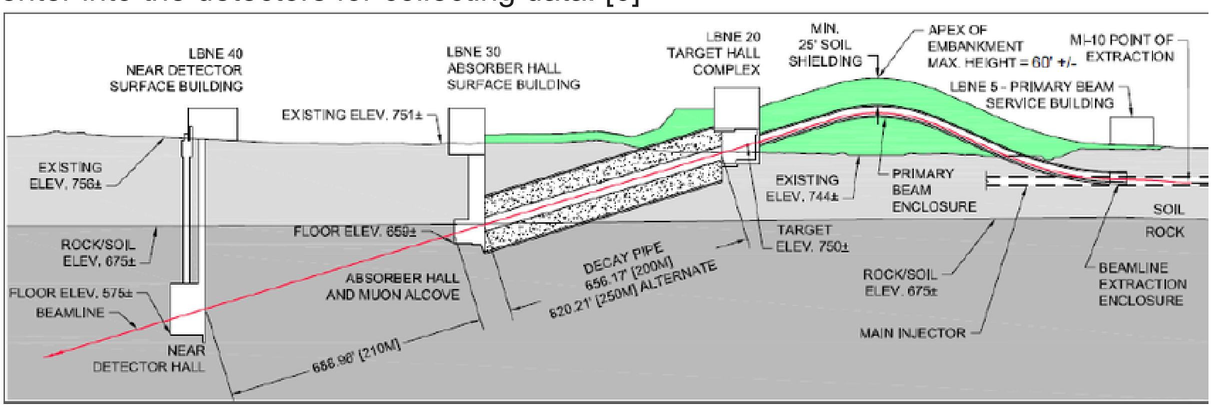

FIG. 2. The figure shows the process to form a neutrino beam in the Deep Underground neutrino experiment. .

Low energy excess

In 2001, there was an abnormal ν_{e} excess event count discovered in the Liquid Scintillator Neutrino Detector Experiment（LSND experiment). In the experiment, there is a 129 ± 43 number of excess events that don’t correspond to the prediction made by the three neutrino models. The LSND experiment measured Δm^{2} as approximately $1eV^{2}$, which is higher than the mass square splitting of Δm_{12} and Δm_{23}. Due to the phenomenon happened in the LSND experiment, a hypothesis was postulated that the bias of different amount of excess events caused by the existence of another kind of neutrino, which is the sterile neutrino. [7] [2] [9] The existence of sterile neutrinos had been proposed for about 40 years before the experiment. This generated new interest in low energy excess.

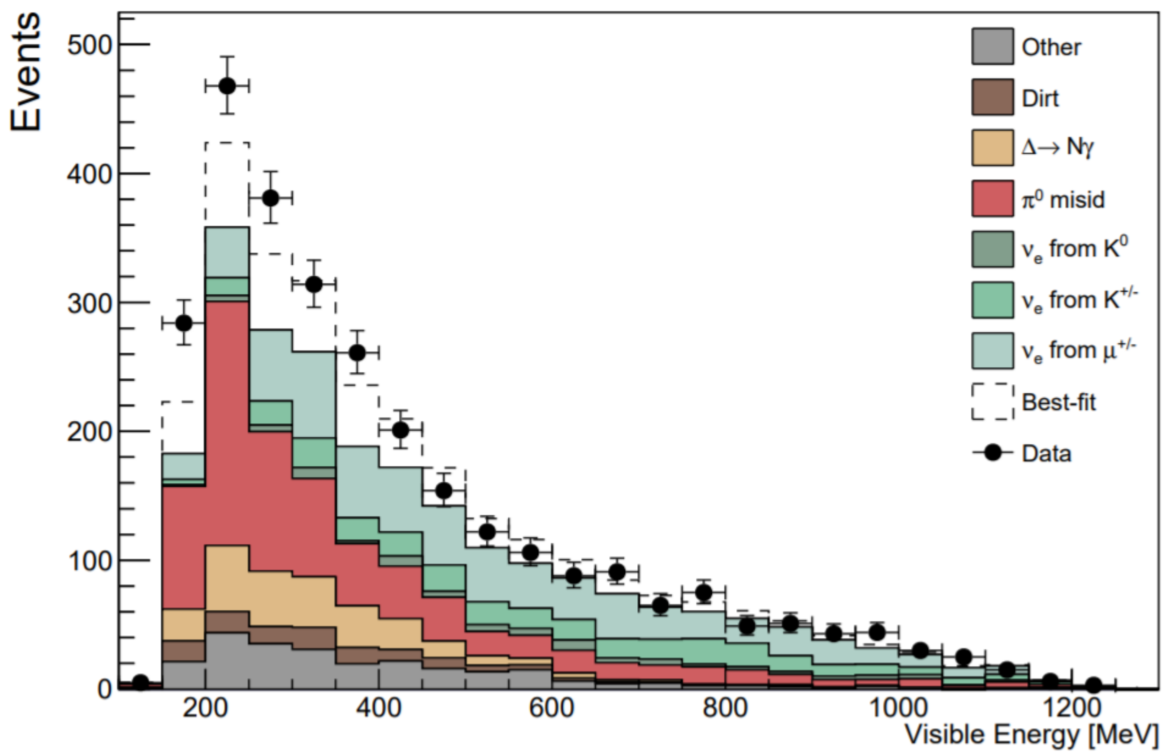

FIG. 3. This figure shows the frequency of events in different visible energy with staitistical error. The data dot represent the data collect by MinibooNE. The histogram represent the prediction calculated by the three neutrino model.

To explore the low energy excess, the MinibooNE experiments began collecting data from 2002. MinibooNE is a spherical neutrino detector with a diameter of 12.2 meters. Instead of argon, it is filled with 818 tons of mineral oil and lined with 1,280 photomultiplier tubes. [1] In the experiment, physicists in Los Alamos conducted an experiment with MinibooNE to observe the neutrino oscillation transform from muon neutrino to electron neutrino by observing the muon decay [2] $\mu^{+} \rightarrow e^{+} + v_{e} + \bar{\nu}_{\mu}$.

Figure 3 shows an overall result of the MinibooNE experiment. When the visible energy is larger than about 475 MeV, the data collected from the MinibooNE experiment and the prediction calculated by three neutrino models are consistent with each other. However, when the Visible energy is below 475 MeV, It shows a significant excess of interaction times, which is 38.6 ± 18.5 excess events. [6] The statistical significance is 4.8σ, which is very high. [2]

II. DATA ANALYSIS

In MicrobooNE, data was collected in seven channels filled with Booster Neutrino Beams (BNB). The data was analyzed by a fully 3+1 neutrino oscillation model. the BNB flux is composed of ν_e and ν_μ . The ν_e s are created during the neutrino oscillation that transform ν_μ to ν_e.Since the proportion of intrinsic ν_e in the BNB flux is very low, the ν_μ appearance effect can be ignored, which enhances the accuracy while analyzing neutrino oscillation. [5]

The neutrino mixing of the 3+1 neutrino oscillation model can be expressed by an unitary Pontecorvo-Maki-Nakagawa-Sakata matrix(U) which also shows the mixing angles between the 4 neutrino flavors. The elements of the matrix is shown as:

$$\left|U_{e4}\right|^2 = sin^2\theta_{14},$$

$$\left|U_{\mu4}\right|^2 = cos^2\theta_{14}sin^2\theta_{24},$$

$$\left|U_{s4}\right|^2 = cos^2\theta_{14}cos^2\theta_{24}cos^2\theta_{34}$$

The U_{s4} refers to the transformation between the sterile neutrino and the fourth mass eigenstate. θ_{14}, θ_{24}, and θ_{34} refers to the corresponding mixing angles. [5]

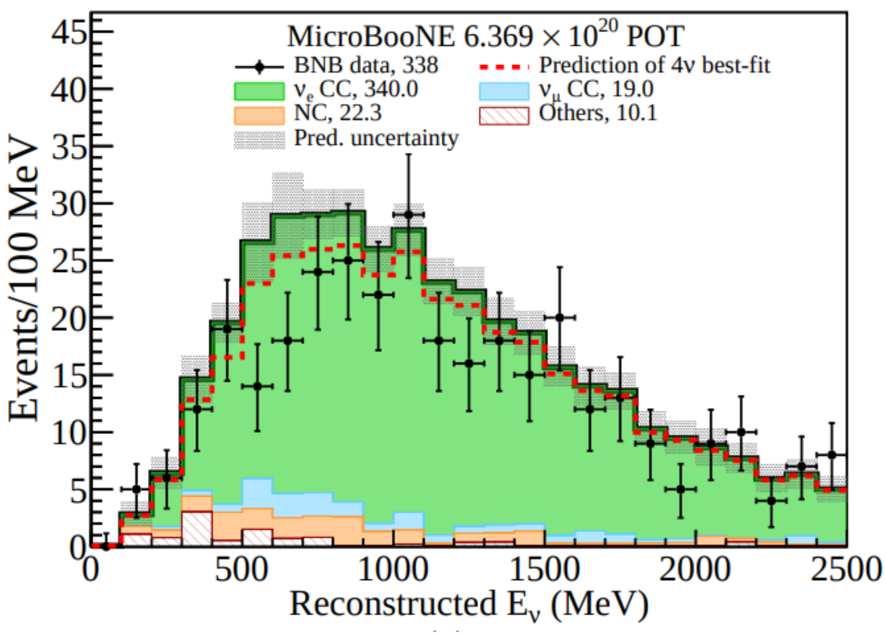

FIG. 4. This figure shows the frequency of events (ve energy spectra) in different reconstructed neutrino energy that fully contained Charged current interaction.

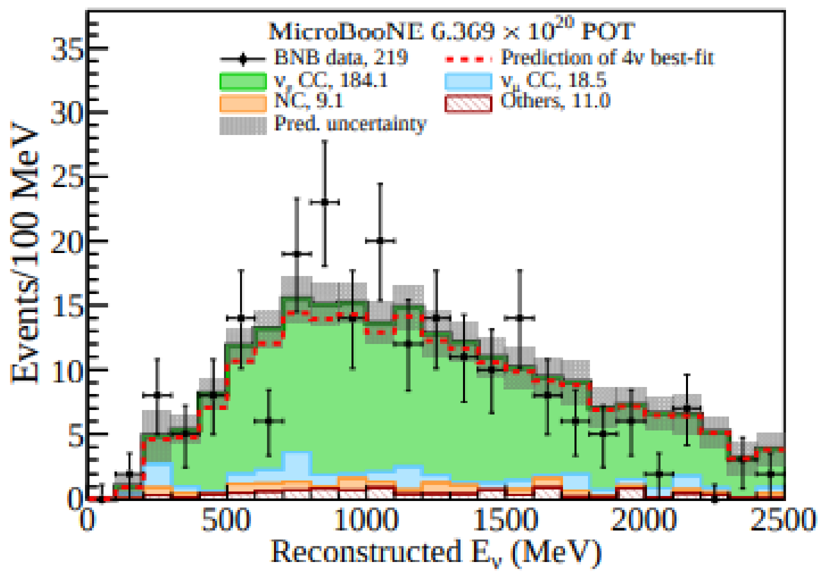

FIG. 5. This figure shows the frequency of events(ve energy spectra) in different reconstructed neutrino energy that paratially contained Charged current interaction.

After combining the seven channels, they found out a best fit result which is: $\Delta m_{41}^{\ 2} = 1.295 eV^2$, $sin^2\theta_{14} = 0.936$, $and\ sin^2\theta_{24} = 0$. Figure 4 and Figure 5 show the ν_e energy spectra in each reconstructed E_ν. This set of data is in a close agreement with the 3ν model at only 1σ significance, which means it doesn't reveal the existence of sterile neutrinos. [5]

Since the outcome tends to agree with the 3 neutrino model, the frequentist-motivated CLs method has been applied to find an estimated range. The confidence level in the context of $\Delta X_{CL}^{\ 2} = X_{4\nu}^{\ 2} - X_{3\nu}^{\ 2}$ is calculated by the formula $CLs = \frac{1-p_{4\nu}}{1-p_{3\nu}}$. The frequentist confidence level contour with 95% confidence level of $(\Delta m_{41}^{\ 2}, sin^2 2\theta_{ee})$ and $(\Delta m_{41}^{\ 2}, sin^2 2\theta_{\mu e})$ has been shown by Figure 6 (a) and (b) respectively. The LSND allowed region in Figure (a) only considers the appearance of v_e. By using the blue and gray area, it shows the 90% and 99% confidence level region. In Figure (b), The blue region shows the 2σ allowed regions of the result of GALLEX, SAGE, and BEST, and the 2σ allowed regions of the Neutrino-4 experiment. [5]

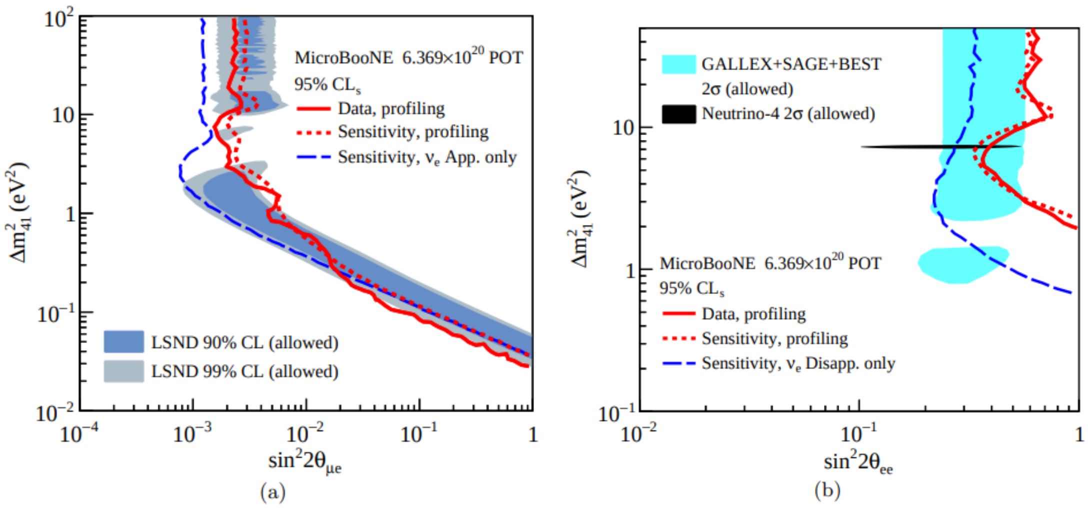

FIG. 6. figure (a) and (b) shows the CLs exclusion contours at the plane with 95% confidence level.

III. CONCLUSION

In conclusion, MIcrobooNE plays a crucial role in finding sterile neutrinos. It is composed of several important components: the light collection system, UV laser system, and cosmic ray tagger system. They all provide unique functions to reconstruct the electric signal or eliminate the cosmic background. As a TPC, the liquid argon also provides it with a great capability of reconstruction. Although there is no conclusive evidence found in MicrobooNE to prove the existence of sterile neutrinos yet, the results provide us with a restriction that narrows down the region where we are more likely to find them. They are great experiences we can learn from to continue future SBN and DUNE experiments.

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