Study of Muon Neutrino Oscillations using MicroBooNE Data

Ellis Huntley
The University of Manchester

(This experiment was performed in collaboration with Alexander Todd)
(Dated: March 1, 2023)

Data collected by the MicroBooNE liquid argon detector was used in a search for eV-scale sterile neutrino oscillations within the 3+1 active-to-sterile framework. Through the consideration of charged-current ν_μ disappearance, parameters squared mass splitting Δm^2_{14} and the neutrino mixing angle $\theta_{\mu e}$ were varied and used to produce contours at the 90% confidence level. No evidence of light sterile neutrinos was observed and regions of parameter space that previously allowed for their existence, based on MiniBooNE and LSND analyses, were excluded. The accuracy of the experiment is largely affected by the utilisation of a uniform 15% error across all data, constituting the primary source of error. To improve the precision of the results, a detailed assessment of the systematic uncertainty must be conducted as part of subsequent analysis.

I. INTRODUCTION:

Most neutrino oscillation results are consistent with the three-flavour neutrino framework, but recent experimental anomalies have motivated a search for light, sterile neutrinos [1]. One such anomaly includes the gallium anomaly, given by results from SAGE and BEST, which detected a deficit of ν_e from radioactive sources [2][3]. These results could be explained by the disappearance of neutrinos via oscillation into a sterile state, the discovery of which would have far-reaching implications in fundemental physics.

MicroBooNE's detector is a liquid argon time projection chamber with dimensions of 10.4 m in length, 2.6 m in width, and 2.3 m in height [4]. The neutrino beam is generated by a beryllium target, found 468.5 m from the detector, which is struck by protons. This produces secondary hadrons which, in turn, produce a neutrino beam through their decay [5]. Interactions that occur within the detector are detected by three wire planes, each orientated in a different direction.

The purpose of this experiment is to evaluate the possible existence of sterile neutrinos by considering ν_μ disappearance using MicroBooNE data. Finally, to compare the excluded variable parameter space to previous MiniBooNE and LSND results.

II. THEORY

A. 3-Flavour Neutrino Oscillation

Neutrinos are neutral, spin-1/2 particles and can have three different flavours: electron, muon and tau [6]. As a solution to the 'Solar Neutrino Problem', the idea of neutrino oscillations was introduced [7]. This idea postulates that neutrino flavour eigenstates exist in a superposition of mass eigenstates, governed by the PMNS matrix, U^{PMNS} [8][9]. This superposition is given by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \tag{1}$$

where $\nu_{e,\mu,\tau}$ are the flavour eigenstates and $\nu_{1,2,3}$ are the mass eigenstates. In the two-flavour approximation, equation 1 is written as

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}, \tag{2}$$

where θ is known as the mixing angle. From equation 2, the time propagation of the state is given by

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle, \tag{3}$$

$$|\nu(t)\rangle = e^{q_1\cdot x}\cos\theta\,|\nu_1\rangle + e^{q_2\cdot x}\sin\theta\,|\nu_2\rangle, \tag{4}$$

where $q_{1,2}$ are the time propagated four-momenta. Using equations 3 and 4, the probability of two-flavour oscillation is calculated to be

$$P(\nu_{\alpha\to\beta}) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{21}(\text{eV})^2 L(\text{km})}{E(\text{GeV})}\right) \tag{5}$$

where Δm^2_{21} is the squared mass splitting, L is the distance travelled by the neutrino and E is the neutrino energy.

B. 3+1 Active-To-Sterile Framework

The 3+1 framework assumes the existence of a fourth, sterile neutrino ν_s and now equation 1 is modified to be

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}. \tag{6}$$

To compare to MiniBooNE and LSND analyses, it is required that ν_μ disappearance parameter space be converted into ν_e appearance parameter space. Using the relevant matrix elements U_{e4} and $U_{\mu 4}$, the probability of oscillation is now given by

$$P(\nu_{\mu\rightarrow e}) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\frac{\Delta m^2_{14}L}{E}\right), \qquad (7)$$

where all quantities are in the units stated previously.

III. METHOD AND ANALYSIS

A. Data Selection

The MicroBooNE data used in this analysis contains 15 different features used to describe the interactions within the detector. The significance of each feature was quantified in order to sensibly reduce the data for consideration of ν_μ disappearance. This was done by utilising a gradient boosting classifier (GBC). GBCs make predictions by using shallow decision trees generated sequentially that have the ability to correct the previous trees' errors [10]. They are very sensitive to the hyperparameters, but properly calibrated GBCs are incredibly powerful classifiers, thus making them a natural choice for high energy physics [11][12]. In this analysis of MicroBooNE data, the GBC outperformed the alternative, a random forest, by producing a confusion matrix whose diagonal elements were closer to 1. The confusion matrix can be seen in figure 1.

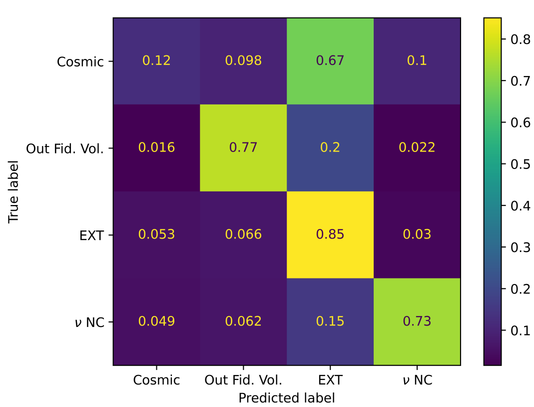

FIG. 1. Confusion matrix for the gradient boosting classifier model. Each element shows the probability that the truth data matches what the model predicts, with values close to 1 in the diagonals indicating an accurate model. In this case, both cosmic and the off-beam data, labelled Cosmic and EXT respectively, contain cosmic muons, thus the model struggles to distinguish the two categories.

Using the GBC, the importance of each feature in the data was determined, with the most important feature found to be topological score. The topological score serves as a valuable metric for capturing the trajectory of a signal in the detector. Given that different particle exhibit distinct tracks, it is unsurprising that this feature has been identified as the most important.

In this experiment, only ν_μ disappearance is considered, so the data was cut to maximise these events. When cutting data, both efficiency and purity must be considered, with these being defined as

$$\text{Efficiency} = \frac{\text{Events surviving the selections}}{\text{Total number of events}}, \qquad (8)$$

$$\text{Purity} = \frac{\text{Signal events surviving selection cuts}}{\text{Total events in selected sample}}. \qquad (9)$$

The first cuts removed unphysical values, then subsequent cuts were implemented to remove as much background as possible, whilst also attempting to maximise the product of equations 8 and 9 in accordance with standard practice. The cuts for each feature were made by descending importance. With all of the selections implemented, a histogram of the reconstructed neutrino energy was produced, shown in figure 2. The error on each bin was approximated to be a flat systematic uncertainty of 15%, combined with the statistical uncertainty.

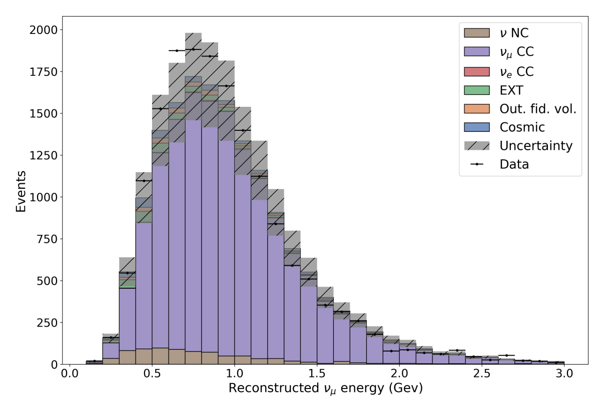

FIG. 2. Reconstructed neutrino energy, displaying the generated Monte Carlo data as colored bars, accompanied by the actual data collected by MicroBooNE represented as horizontal lines.

These results could be improved by dedicating additional time to optimising the GBC. Although a grid search was employed to identify hyperparameters that enhanced the model, a more comprehensive optimisation could not be conducted due to time constraints. Using a finely tuned GBC would allow the selection cuts to be automated by using the model's score, as opposed to simply using importance as an indicator, which is what was done in this analysis.

B. Parameter Space Exclusions

The Monte Carlo data was scaled according to equation 7 by varying Δm^2_{41} and $\sin^2(2\theta_{\mu e})$. The χ^2 value for the scaled Monte Carlo's fit to the real data was calculated for each variation. The minimum χ^2 yields best fit parameters of $\Delta m^2_{41} = 14.2$ eV^2 and $\sin^2(2\theta_{\mu e}) = 0.0464$. This is consistent since figure 2 does not show any evidence of event deficit, and the best fit values correspond to minimal oscillation. Using the χ^2 values, a contour of the 90% confidence level was plotted with the MiniBooNE and LSND data [13][14].

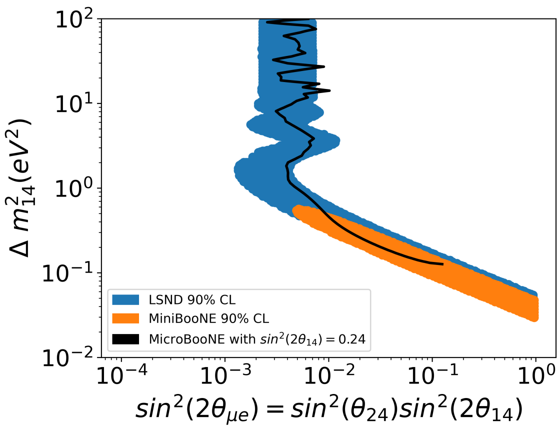

FIG. 3. The 90% confidence levels for MiniBooNE, LSND and MicroBooNE in the 3+1 framework. The MiniBooNE and LSND levels fill the region in parameter space in which a sterile neutrino is allowed to exist. The exclusion zone is set to be beyond 90% confidence level.

This analysis finds no evidence of sterile neutrinos and, as seen in figure 3, some of the previously allowed parameter space given by MiniBooNE and LSND has been excluded with 90% confidence. These results are consistent with previous MicroBooNE analysis [5].

To improve the accuracy of these results, a better estimation of the systematic uncertainties is required. The current approach employs a flat 15% across the data, which does not account for the full range of factors that will contribute to the uncertainties. Conducting a more detailed assessment will likely shift the confidence level and will exclude a larger region in parameter space.

IV. CONCLUSION

The search for eV-scale sterile neutrino oscillations within the 3+1 active-to-sterile framework using data collected by the MicroBooNE liquid argon detector did not yield any evidence of light sterile neutrinos. Contours drawn in the plane of Δm^2_{14} and $\theta_{\mu e}$ excluded, with 90% confidence, regions of parameter space that MiniBooNE and LSND had allowed for their existence. The dominant source of error in this analysis was the utilisation of a systematic 15% uncertainty, which is unlikely to be an accurate estimation. Future analysis would require a thorough evaluation of the systematic uncertainties and would likely lead to an increase in the size of the exclusion zone. Furthermore, additional time for the optimisation of the GBC would allow for considerably more accurate data selection, which would certainly yield better results.

[1] P. Adamson, F. An, I. Anghel, *et al.*, Improved constraints on sterile neutrino mixing from disappearance searches in the minos, minos+, daya bay, and bugey-3 experiments, Physical review letters **125**, 071801 (2020).

[2] V. V. Barinov, B. Cleveland, *et al.*, Results from the baksan experiment on sterile transitions (best), Physical review letters **128**, 232501 (2022).

[3] J. Abdurashitov, V. Gavrin, *et al.*, Measurement of the solar neutrino capture rate with gallium metal, Physical Review C **60**, 055801 (1999).

[4] R. Acciarri *et al.*, Design and construction of the microboone detector, Journal of Instrumentation **12** (02), P02017.

[5] P. Abratenko, D. A. Aldana, *et al.*, First constraints on light sterile neutrino oscillations from combined appearance and disappearance searches with the microboone detector, Physical Review Letters **130**, 011801 (2023).

[6] P. D. Group *et al.*, Review of particle physics, Progress of Theoretical and Experimental Physics **2020**, 1 (2020).

[7] M. Nakahata, History of solar neutrino observations, Progress of Theoretical and Experimental Physics **2022**, 12B103 (2022).

[8] G. Bellini, L. Ludhova, *et al.*, Neutrino oscillations, Advances in High Energy Physics **2014**, 1 (2014).

[9] S. Kornowski, The pmns neutrino-mixing matrix in the scale-symmetric theory, The Scale-Symmetric Physics **674** (2017).

[10] A. Singh *et al.*, A review of supervised machine learning algorithms, in *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)* (Ieee, 2016) pp. 1310–1315.

[11] R. Caruana *et al.*, An empirical comparison of supervised learning algorithms, in *Proceedings of the 23rd international conference on Machine learning* (2006) pp. 161–168.

[12] B. Roe *et al.*, Boosted decision trees as an alternative to artificial neural networks for particle identification, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **543**, 577 (2005).

[13] A. Aguilar, L. Auerbach, *et al.*, Evidence for neutrino oscillations from the observation of ν e appearance in a ν μ beam, Physical Review D **64**, 112007 (2001).

[14] A. Aguilar *et al.*, Updated miniboone neutrino oscillation results with increased data and new background studies, Physical Review D **103**, 052002 (2021).