IMPERIAL

# Searching for sterile neutrinos C2

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The following experiment guide is NOT intended to be a step-by-step manual for the experiment but rather provides an overall introduction to the experiment and outlines the important tasks that need to be performed in order to complete the experiment. Additional sources of documentation may need to be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must be cited in the references of the report.

# Contents

# 1 Introduction

In this experiment we will look at data taken at neutrino experiments, and use it to make some state-of-the-art particle physics measurements. The MicroBooNE experiment has recently released a dataset containing muon-type neutrinos. We will look for evidence of the oscillations of the flavour of neutrinos.

Particle Physics is the study of the elementary building blocks of the universe (particles) and the fundamental forces that govern their behaviour. We have developed a mathematical model that describes these called the Standard Model (SM) of Particle Physics. This model is excellent in many areas, for example the gyromagentic ratio of the electron (which quantifies how fast an electron will precess in a magnetic field) agrees between experiment and theoretical prediction to 15 decimal places with the two values compatible within measurement and prediction uncertainties. The Standard Model is one of humanity's greatest achievements in understanding the nature of the universe.

As good as it is, we do not believe the Standard Model is the ultimate description of reality. Attempts to incorporate gravity into the standard Model have failed. The masses and charges of the particles must be measured experimentally. The answer to "Why we have the three seemingly identical "generations" of particles?', 'Why do they split into quarks and leptons?', and 'Why is charge quantised?' are completely unknown. Of particular relevance here is that the Standard Model treats neutrinos as massless. As we will see, the observation of neutrino oscillations requires some neutrinos to have mass. This raises questions about the origin of their masses; if their mass is generated in the same way as for other the other fundamental particles (the Higgs mechanism) a non-interacting, but so-far unobserved, neutrino is required. Alternatively, another mechanism is required.

The general consensus is that the Standard Model is incomplete, with the expectation being that it is the low-energy approximation of some more complete theory that has fewer of these unanswered questions. If one extends the Standard Model to make it more complete, that will come with new particles and/or forces of nature. It is the goal of experimentalists to find hints of this so-called physics Beyond the Standard Model (BSM).

Neutrino oscillations are a natural place to look for signs of BSM physics, as the origin of their mass is currently not adequately addressed in the model. Insights made in this area could point the way to the direction the model must be extended.

# 2 Neutrinos in the Standard Model

Neutrinos are the only neutral fundamental fermions known. There are three neutrinos, each paired with one of the leptons, electron ($e^{\pm}$), muon ($\mu^{\pm}$) and tau ($\tau^{\pm}$). In the Standard Model neutrinos are neutral, so don't interact with the electromagnetic force; and they are leptons, so don't interact with the strong nuclear force. The only force they are known to experience is the weak nuclear force (although it is assumed they experience gravity too). These are interactions with the $W^{\pm}$ boson, a charged lepton and a neutrino or with the $Z^0$ boson, and two neutrinos. Some examples of these interactions are shown in figure 1. The leptons on both legs (muons in the diagram) must be the same, so electrons interact with electron neutrinos, muons with muon neutrinos and taus with tau neutrinos. As they only interact weakly, the probability of seeing a given neutrino in a detector is very small. Most early measurements of neutrinos were inferred from the unobserved energy and momentum carried away in, for example, $\beta$ decays.

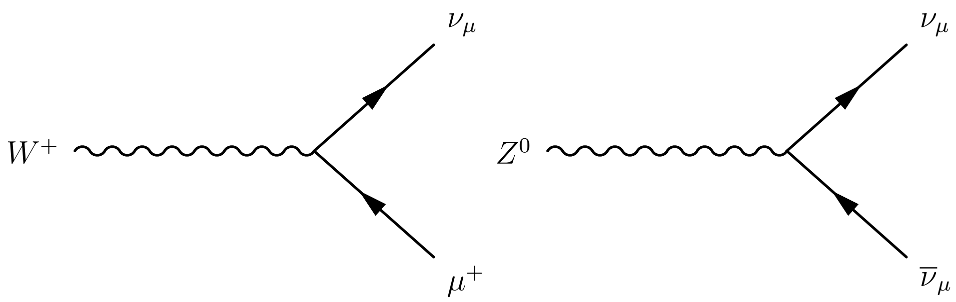


Figure 1: The interaction of a $W^+$ boson, an anti-muon, and a muon neutrino known as a "charged-current process" (left), and the interaction of a $Z^0$, a muon neutrino and a muon anti-neutrino known as a "neutral-current process" (right).

Fermions are quite complicated mathematically, however they can always be split into two components. These parts are called left and right-handed components (you don't need to understand exactly what this means, but fundamentally there are two ways a fermion can be Lorentz boosted, and these are the components of a general fermion that are boosted in each way). If fermions were massless the left-handed and right-handed components would evolve separately as two distinct particles. The action of mass is to mix the two states together. Electromagnetism and the strong force interact equally with left and right-handed states, however the weak force only interacts with left-handed particle states. As neutrinos only interact with the weak force, only left-handed neutrinos are known to exist, and so the Standard Model does not include right-handed neutrinos required to give them mass.

# 3 Direct Neutrino Detection

Direct measurements of neutrinos are carried out by measuring the number of neutrinos that interact from a source that produces vast numbers of them. These interactions are those shown in figure 1. In a charged-current interaction the incoming neutrino will produce a lepton of the same type that can be seen in the detector, and the emitted $W$ boson will transfer energy to the nucleus (changing the number of protons in the nucleus and perhaps breaking it apart) or atomic electrons of the material in the detector (making them detectable). In a neutral-current interaction, the incoming neutrino emits a $Z^0$ boson, which again imparts energy to the detector material, however the neutrino then leaves so doesn't produce a lepton directly. If you can identify the type of lepton produced, then charged-current interactions are a direct measurement of the type of neutrino that interacted with the detector. Neutral current interactions can be useful to measure the total number of neutrinos, regardless of type.

There is conveniently an enormous source of neutrinos at the centre of our solar system. The nuclear interactions that power the sun generate a vast number of electron neutrinos that stream through the earth. Measurements of the flux at the earth were lower than the prediction from models of the nuclear reactions in the core of the sun by about a factor of three, the so-called Solar Neutrino Problem. The SNO experiment was able to resolve this problem by showing that the missing electron type neutrinos had oscillated to muon and tau type neutrinos. In the next section we will show that this requires some of the neutrinos to be massive.

## 4 Neutrino Oscillations

To show the origins of neutrino oscillations we will assume that there are three mass states, $\nu_1$, $\nu_2$ and $\nu_3$ (this is how the neutrinos propagate) and these are linear combinations of the interaction states $\nu_e$, $\nu_\mu$ and $\nu_\tau$ (this is how the neutrinos interact with weak bosons), such that

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

where $U^{\mathrm{PMNS}}$ is known as the PMNS matrix. **NB This may seem like a strange situation (indeed it is!), but it has also been shown to be true of the quarks with the analogous CKM matrix.** It can be a little unwieldy to work with three neutrinos, the relevant concepts will be apparent with just two neutrinos

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

This gives an initial $\nu_\alpha$ state as

$$\begin{aligned}
|\nu_\alpha\rangle &= \cos\theta \; |\nu_1\rangle + \sin\theta \; |\nu_2\rangle \\
|\nu_\alpha(t)\rangle &= \cos\theta \; |\nu_1(t)\rangle + \sin\theta \; |\nu_2(t)\rangle \\
|\nu_\alpha(t)\rangle &= \cos\theta \; e^{i(E_1 x - pt)} \; |\nu_1\rangle + \sin\theta \; e^{i(E_2 x - pt)} \; |\nu_2\rangle \\
|\nu_\alpha(t)\rangle &= \cos\theta \; e^{i(E_1 x - pt)} \; (\cos\theta\,|\nu_\alpha\rangle - \sin\theta\,|\nu_\beta\rangle) \\
&+ \sin\theta \; e^{i(E_2 x - pt)} \; (\cos\theta\,|\nu_\beta\rangle + \sin\theta\,|\nu_\alpha\rangle)\,.
\end{aligned}$$

From this, one can show the probability of finding an initial $\nu_\alpha$ state with energy E, in a state $\nu_\beta$ some distance $L$ from the production site is

$$P(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta|\nu_\alpha\rangle|^2 = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m_{21}^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right),$$

where $\Delta m_{21}^2 = m_2^2 - m_1^2$ is the difference of squares of the masses of the two mass eigenstates. It is useful to try to derive this, and discuss the implications with a demonstrator.

**The important implication is that this probability is only non-zero if the masses are different. So if an initial state is seen as a different state later, at least one of the neutrinos must be massive.**

## 5 Measuring Oscillation Parameters

In this experiment we will be looking at data generated from a beam of initially muon-type neutrinos produced at Fermilab interacting with a detector 470 m away called MicroBooNE, with the goal of determining the mass and PMNS-matrix parameters – collectively known as *oscillation parameters*.

Details of how the MicroBooNE detector measures neutrino interactions can be found in Appendix A, and the parameters it computes associated with those interactions can be found in Appendix B.

The MicroBooNE experiment is sensitive to charged-current interactions that produce electrons and muons; the incoming energy of the neutrinos is too low to create tau leptons. If one can identify the resulting muons, one can infer the number of muon-type neutrino that have interacted with the detector, and by comparing to an expected number deduce how many of the initial muon-type have oscillated to another type.

The probability of an initial muon-type neutrino being later detected as a muon-type neutrino depends on the energy of the neutrino. So the comparison of the initial and observed neutrino numbers must be done as a function of energy. This probability also depends on the mass and PMNS-matrix parameters $\Delta m_{12}^2$ and $\sin^2(2\theta)$. If one can find the values of these parameters that best describe the observed data, then one has (probabilistically) measured these values. Interpreting these results is an interesting statistical problem, and is discussed in Appendix D.

The interactions measured in the MicroBooNE detector are not all from $\nu_\mu$ interactions; No method for identifying them can ever be perfect. The sources of these so-called background events is discussed in Appendix C, and the impact of these needs to be reduced and accounted for.

The physics goal of the MicroBooNE experiment is actually not to look for $\nu_\mu$ oscillating to $\nu_e$ or $\nu_\tau$, but to a hypothetical fourth type of neutrino that doesn't interact via the weak force (in addition to not interacting through the electromagentic and strong forces). These are known as sterile neutrinos. Results from the MiniBooNE and LSND experiments, which saw more electron-type events than expected, were consistent with the expectation for oscillations including a sterile neutrino. A discussion of how to interpret the data in searching for these sterile neutrinos can be found in Appendix E.

# 6 Datasets

The dataset can be accessed from the OneDrive link below, there are three pickle files each containing a pandas DataFrame, where the row contains the information about a single candidate. The files are:

**Simulation.pkl** This contains simulated data of the detector response with the expected flux of $\nu_\mu$ passing through the detector under the assumption of no oscillations. The file includes contamination from $\nu_e$, cosmic ray interactions and data taken while the neutrino beam is off. A flag is present in this sample to label the types of events, with the flag taking the values:

| Category | Interaction | Meaning |
|---|---|---|
| 4 | Mis-ID | Cosmic events misidentified as neutrino events |
| 5 | Out Fid. Vol. | Events occurring within the outer fiducial volume |
| 7 | EXT | Events detected when the neutrino beam is off |
| 10 | $\nu_e$ CC | Electron neutrino events |
| 21 | $\nu_\mu$ CC | Muon neutrino events |
| 31 | $\nu$ NC | Neutral current neutrino events |

The accuracy of the simulation is dependant on a number of external inputs, for example the interaction cross-section of a neutrino with an argon nucleus. One may assume there is a 15% uncertainty over small regions of neutrino energy, and that this uncertainty is not correlated between these regions of energy.

**OscillatedSimulation.pkl** This contains a simulated dataset of $\nu_\mu$ interactions, under the assumption of one set of oscillation parameters.

**Data.pkl** This contains the actual detector response of the MicroBooNE detector subject to the initially $\nu_\mu$ beam.

Two additional files are available for use in the same OneDrive folder

**Result_LSND.pkl** This contains the 90% confidence level result from the LSND analysis, for comparison.

**Result_MiniBooNE.pkl** This contains the 90% confidence level result from the MiniBooNE analysis, for comparison.

**Link to OneDrive location with data set:** 3rd Year Labs - Particle Physics Data

**Link to GitHub location with examples:** GitHub Repo

# 7 Tasks

1. Make histograms for the variables in the simulated dataset. Isolate samples of muon-type interactions, compare the distributions to those from other types of interactions, and determine if any of the variables have the potential to discriminate between them.

2. Devise a selection that can enhance the purity of the muon-type interactions in the sample. Consider if this selection is 'optimal' for determining the oscillation probabilities in terms of statistical and systematic uncertainties. You should discuss this with a demonstrator.

3. Devise a way to adjust the shape of the simulated $\nu_\mu$ energy spectrum to account for different sets of oscillation parameters.

4. Use a $\chi^2$ test to compare the distributions of a given set of parameters with another dataset, and test a few parameters on the simulated oscillated dataset. You should see some parameters provide better agreement (lower $\chi^2$) than others.

5. By finding the set of parameters that give the best agreement, determine the oscillation parameter in the simulated oscillation set. How might one attribute an uncertainty to this determination. Discuss this with a demonstrator.

6. Determine the oscillation parameters and their uncertainty from the MicroBooNE dataset.

7. **Extension 1: Sterile combination** Reinterpret the result together with LSND and MiniBooNE results to obtain an exclusion plot for a 4th, *sterile*, neutrino.

# A Reconstruction

The MicroBooNE detector is made from 170-tons of liquid argon formed into a time projection chamber (TPC). Here we will briefly describe how the detector works and can provide information about interacting neutrinos. A schematic diagram of the detector can be see in Figure 2.

## Scintillation and ionisation

A charged particle travelling through material can interact electromagnetically with the atomic electrons of the material. This interaction will impart some energy to the atomic electrons. If the amount of energy is not enough to free the electron from the atom, the electron returns to the ground state emitting a photon. This is known as *scintillation*. If the energy is enough to free the electron so it can travel through the detector on its own, this is known as *ionisation*.

The photons emitted by the scintillation process travel in all directions. They may be measured by photomultiplier tubes (PMTs) at the edges of the detector. As the scintillation process is fast, and photons travel at the speed of light, the signal from scintillation can give useful timing information for when a particle interacted with the detector.

The electrons emitted from ionisation are more complicated to measure. The MicroBooNE detector applies an electric field through the liquid-argon volume. These electrons accelerate in the field towards one edge of the detector, and as they gain energy have the ability to liberate further electrons that also accelerate. The result is one electron at the production site can become thousands at the edge of the detector, leading to a measurable current in a lattice of wires at the edge. Which wires sense the current can be used to localise the interaction in the plane perpendicular to the electron's acceleration. The ionisation electrons travel much slower than the scintillation photons, but the difference in arrival time between the electrons and photons tells you how far away the initial interaction was. This can be combined with the position of the electron stream in the directions perpendicular to the field. The result is a 4D location of the initial interaction of the charged particle with the detector.

## Finding particles

As the charged particle travels through the detector, some of the points it interacts with the material are determined using the scintillation and ionisation signal. These points map out the trajectory of the particle through the detector, known as a *track*. Reconstruction algorithms are used to turn the collection of interaction points into tracks. It should be noted that there can be multiple particles passing through the detector at the same time, random radioactive decays or thermal noise that can produce signals, so associating these signals with specific tracks is non-trivial and isn't achieved perfectly.

Once the collection of interactions are associated to a track, then the energy deposited in the detector can be measured from the size of the signals, the length of the track (which stops once all the energy has been deposited), and the shape of the track (which is dependent on the momentum and mass of the particle. Faster and heavier particles are bounced around, *scattered*, less by the atoms). This information can be used to determine the initial energy of the charged particle and also its type.

### Finding Neutrino interaction

The specific form of the interactions we're interested are when a neutrino interacts with a nucleus, producing a charged lepton (of the same type as the incoming neutrino), and where enough energy has been transferred to the nucleus to free a proton. This means we should see two charged tracks coming from the same point or *vertex*. Yet more reconstruction algorithms are employed to look for these topologies of two tracks forming a vertex.

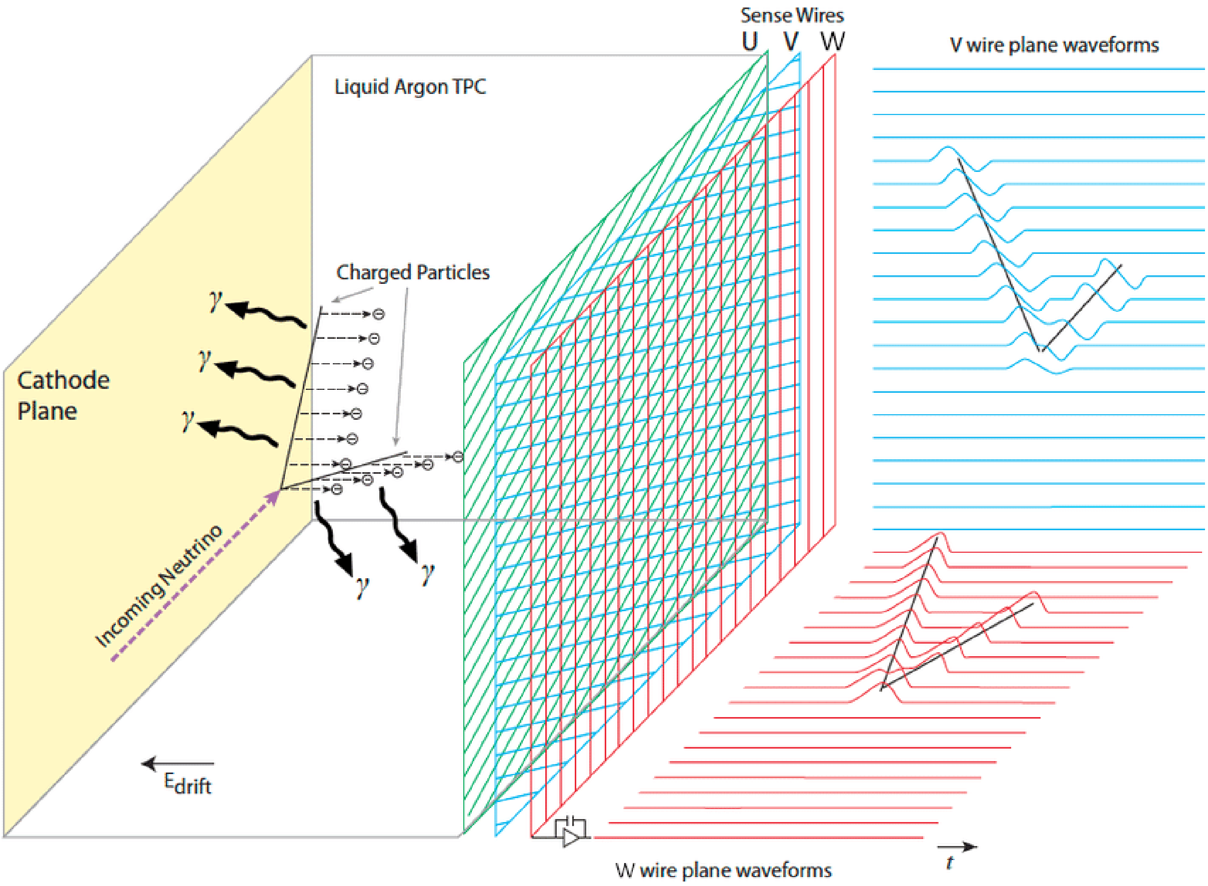


Figure 2: Schematic of the reconstruction of a neutrino interaction with the MicroBooNE time projection chamber. Taken from [2].

# B Variables

The output of the reconstruction discussed in Appendix A is a set of parameters about a suspected neutrino interaction in the detector. These are the position of the reconstructed neutrino interaction vertex. The start and end positions of the associated track and its length. The distance from the interaction vertex to the longest track in the event, and the distance from the interaction vertex to the nearest cosmic-ray muon. The output of an ML algorithm trained to differentiate well defined tracks from showers. The output of an ML algorithm trained to use topological information to identify charged-current muon events. The momentum of the muon reconstructed from the track length and from the particle scattering. The log-likelihood of the track being a muon. The total energy of the reconstructed particles in the interaction, which is the best estimate of the incoming neutrino energy.

All distances are in centimetres and all energies in GeV.

The simulation contains also the simulated energy of incoming neutrino, the simulated flight distance of the neutrino, and the category of simulated process. The simulation also contains a weight that quantifies the relative contribution of that interaction compared to others.

# C Backgrounds

No real-world experiment is perfect. Not all things identified as neutrino interactions are actual neutrino interactions. These act as *backgrounds* to the signals we are interested in, and we will briefly discuss the sources of these backgrounds.

### $\nu_e$ charged current interactions

Some of the neutrinos interacting with the detector are electron-type, these can come from oscillations of the initial muon-type, or from the small $\nu_e$ contamination of the initial beam. These will produce an electron not a muon in the detector, so the level to which these can be suppressed depends of the ability to distinguish those cases.

### Neutral current interactions

Not all neutrino interactions are via the charged current, neutral currents will typically liberate an electron from the atom, or possibly induce some nuclear decay. These again can be suppressed by the ability to identify the muon in the signal decay.

### Cosmic rays

A vast number of cosmic-ray muons reach the earth. Mostly vertical, but scattering from rocks can make some appear from the beam direction. These muons can then leave a track in the detector. If this track is coincident with other activity in the detector, it can be mistaken for our signal. These will typically leave tracks that start close to the edge of the detector, where they enter. So one can define a so-called *fiducial volume*, where one only accepts interactions that start some distance into the detector.

# D Statistics

We will be comparing the predicted reconstructed energy spectrum for sets of oscillation parameters to the observed reconstructed energy spectrum to find the set of parameters (or ranges of these parameters), that best (or statistically) match the data. This is a topic known as hypothesis testing, about which much has been written in the literature. Here we will just look at some important points.

To compare two distributions we want to condense the information into a single number, known as a *test statistic*. You are free to chose your own test statistic, but a fairly standard choice is a binned $\chi^2$, defined as

$$\chi^2 = \sum_i \frac{(N_{\mathrm{obs},i} - N_{\mathrm{pred},i})^2}{\sigma_i^2}\,, \tag{1}$$

where $N_{\mathrm{obs},i}$ is the number of events observed in some small region (bin) of energy, $N_{\mathrm{pred},i}$ is the prediction for the number in that bin, $\sigma_i$ is the uncertainty on the difference in that bin, and the sum runs over all bins. Here it has been assumed that the number of events in the bins and their uncertainties are uncorrelated.

The predicted number is a function of our oscillation parameters, $N_{\mathrm{pred}}(\Delta m^2, \sin^2 2\theta)$, and so then is the $\chi^2$. The values of the oscillation parameters that give the smallest $\chi^2(\Delta m^2, \sin^2 2\theta) = \chi^2_{\mathrm{min}}$ are the best estimates of the parameters. Strictly, this is true in the limit of large statistics but is generally applicable to a wide range of problems. You may want to think about how you could test if this is true in our case.

Under the assumption that it is well behaved, the $\chi^2$ has some nice properties. The difference in the $\chi^2$ between two hypotheses is directly relatable to p-values depending on the number of degrees-of-freedom (or fit parameters) difference there are between the two hypotheses. For example, for one parameter, a $\Delta\chi^2 = 1$ corresponds to a confidence level (CL) of 68%, or equivalently a p-value 0.32, equivalent to the $1\sigma$ region of a normal distribution. In such cases the $\Delta\chi^2 = 1$ region is used to define the $1\sigma$ uncertainties. The $\chi^2$ corresponding to particular p-values and degrees of freedom are available in tables, and computable using standard software packages.

Another useful $\chi^2$ property is that its absolute value is a measure of how good the fit is. Each term in the sum should have an expectation of 1 (it is worth convincing yourself of this), and so the $\chi^2$ should be around the number of bins (minus the number of fit parameters that have been determined from that data).

Due to statistical fluctuations, systematic effects, etc, it is possible that the set of parameters that give the best $\chi^2$ don't fall within the range of physically meaningful parameters. For e.g. if the number of $\nu_\mu$ in the data fluctuated up, the fit would prefer $\nu_\mu$ to appear from nothing rather than to have oscillated away, giving a negative value of $\sin^2 2\theta$, which is nonsensical within our model. In these kinds of cases, rather than quoting a result and an uncertainty one instead interprets the result as excluding regions of the parameter space to some confidence level. One may again use the $\chi^2$ to compare two hypotheses. In this case the best fitting of the physical parameters and any other set of parameters. That set of parameters with a $\Delta\chi^2 < \chi^2_{\mathrm{threhold}}$, form the region consistent with the data to whichever confidence level $\chi^2_{\mathrm{threhold}}$ is set to produce. Or equivalently, the points outside of that region are said to have been excluded by the data to that level. Typical confidence levels used are 90% and 95%.

# E Sterile neutrinos at short baseline experiments

In the two neutrino model discussed above, the analysis studies $\nu_\mu \to \nu_\beta$ oscillations, where $\nu_\beta$ can be any flavour state that is not $\nu_\mu$. At "short baseline" experiments like MicroBooNE, these oscillations are particularly sensitive to sterile neutrino related transitions. A *sterile neutrino* is a hypothetical particle that behaves like the known neutrinos (in this context often called *active neutrinos*) except it doesn't even interact with the Weak force. Models that include the three active neutrinos and one sterile neutrino are know as 3+1 models.

Another approach to interpreting the data is to consider the oscillations to all neutrinos separately, using more mixing angles $\theta_{ij}$ with $i, j \in [1, 2, 3, 4]$. These describe the mixing of the mass eigenstates $\nu_i$ and $\nu_j$, however what we actually observe is flavour eigenstates e.g $\nu_\mu$. We therefore re-parameterise $\theta_{ij}$ to $\theta_{\alpha\beta}$ with $\alpha, \beta \in [e, \mu, \tau, s]$.

From an initially $\nu_\mu$ beam this gives us transition probabilities

$$\begin{aligned} P(\nu_\mu \to \nu_\beta) &= \sin^2(2\theta_{\mu\beta}) \sin^2\left(1.27\frac{\Delta m^2_{41} L}{E}\right) \quad \text{and} \\ P(\nu_\mu \to \nu_\mu) &= 1 - \sin^2(2\theta_{\mu\mu}) \sin^2\left(1.27\frac{\Delta m^2_{41} L}{E}\right). \end{aligned}$$

The MiniBooNE and LSND experiments looked for electron appearance events, i.e. $\nu_\mu \to \nu_e$. Their allowed region of parameter space ($\sin^2(2\theta_{\mu e})$ vs. $\Delta m^2_{41}$) can be found in the provided results files. Their results were more consistent with a 3+1 model than a the Standard Model. The question we are concerned with is, if the MicroBooNE data is interpreted in a 3+1 model, is it consistent or not with the MiniBooNE/LSND results? Answering this question can confirm or refute the need for a fourth neutrino.

The two transitions we are concerned with are $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_\mu)$. We note the parameterisation is such that

$$\begin{aligned} \sin^2(2\theta_{\mu e}) &= \sin^2(2\theta_{14}) \sin^2(\theta_{24}) \\ \sin^2(2\theta_{\mu\mu}) &= 4\cos^2(\theta_{14}) \sin^2(\theta_{24}) \left(1 - \cos^2(\theta_{14}) \sin^2(\theta_{24})\right) \\ \sin^2(2\theta_{ee}) &= \sin^2(2\theta_{14}). \end{aligned}$$

Using this, it is possible to recast the MicroBooNE $\nu_\mu$ disappearance such that it can be compared to the MiniBooNE/LSND results directly.

## E.1 Hints

You should think about what probability ($P(? \to ?)$) your current analysis corresponds to here. You could use this paper (or another result of your choice) for a best fit value of $\sin^2(\theta_{14})$. Then, can you derive $\sin^2(2\theta_{\mu e})$ in terms of $\sin^2(2\theta_{\mu\mu})$ and $\sin^2(2\theta_{ee})$? Is it possible to plot $\{\sin^2(2\theta_{\mu e}), \Delta m^2_{41}, \Delta\chi^2\}$? What about other parameters?

# References


[1] J. Waiton *et al*, **"A sterile-neutrino search using data from the MicroBooNE liquid-argon time projection chamber performed in an undergraduate teaching laboratory"** 2025 *arXiv:2509.18859 [physics.ed-ph]* `https://doi.org/10.48550/arXiv.2509.18859`

[2] R. Acciarri *et al*, **"Design and construction of the MicroBooNE detector"** 2017 *JINST 12 P02017* `https://dx.doi.org/10.1088/1748-0221/12/02/P02017`