Neutrino Cross Section Analysis for the MMBC and NOvA Experiments

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A muon detector used to calibrate the MMBC experiment was built. This experiment focuses on measuring hydrogen neutrino cross sections and how it can be applied to further experiments. On the other hand, simulation data from GENIE was used to analyze the expected cross sections in the NOvA experiment by changing the model inputs.

INTRODUCTION

A neutrino cross section is the measurement of probability of the interaction of a neutrino with the target. The cross section σ, can be calculated with the following equation.

$$\sigma = \frac{N}{\phi T} \tag{1}$$

Where N is the number of interactions, T is the number of targets and ϕ is the total flux of incident neutrinos per unit area. Neutrinos are a special kind of particle as they only interact via the weak interaction and gravity. That means neutrinos solely interact by means of W and Z bosons. This gives neutrinos two types of interactions, charged current and neutral current[1].

Neutrinos cross sections are very important because they help with the creation of neutrino oscillation experiments, like NOvA. NOvA is an experiment working on obtaining higher precision measurements of neutrino oscillations which are not predicted by the Standard Model but have been experimentally observed. To do this, NOvA has two detectors: a near detector at Fermilab and a far detector approximately 810 km away in Ash River, Minnesota. These detectors are filled with a liquid plastic scintillator. When neutrinos interact with the atoms in the scintillator, they release particles which are then detected by photo-detectors[2]. Newer neutrino oscillation experiments like DUNE are beginning to use liquid argon instead of plastic. However, other experiments, such as the MMBC, are also looking at liquid hydrogen as a possible candidate for neutrino interactions.

The Modern Modular Bubble Chamber (MMBC) looks to obtain better measurements of hydrogen neutrino cross section to help with the data collection and analysis in various experiments. Hydrogen neutrino cross sections are mainly observed in older bubble-chamber experiments and therefore not a large amount of data is available for analysis. The MMBC will be the first hydrogen bubble chamber to be built in more than 40 years and will reduce the uncertainty of hydrogen cross section. This will be beneficial to experiments like DUNE because hydrogen targets can provide increased sensitivity as opposed to heavier nuclear targets such as argon.

Methods

To analyze neutrino cross sections, two projects were worked on. Firstly, for the MMBC experiment muon detectors are needed to detect cosmic ray background and calibrate the bubble-chamber detectors. Secondly, for the NOvA experiment, analysis of simulations is used to better understand the neutrino cross section models and with that understanding the data obtained from the near detector.

COSMIC WATCH

The type of muon detector being built is called "Cosmic Watch". Cosmic Watch is a project designed by a group of physicists at MIT led by Spencer Axani. Cosmic Watch is a small, cheap and student friendly muon detector.

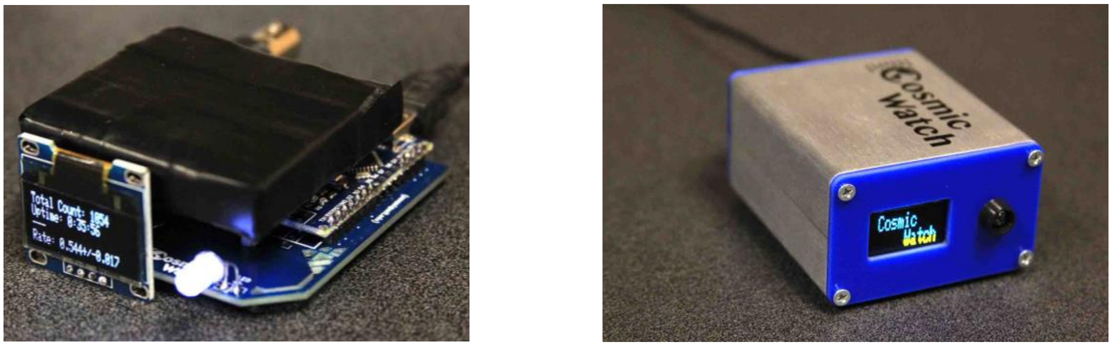
The Cosmic Watch detects muons by using a plastic scintillator. When cosmic rays reach the Earth's atmosphere they collide with particles, creating different particles that "shower" down to the surface. One of these particles is the muon, which reaches the surface of the Earth where it interacts with the Cosmic Watch. The muon enters the plastic scintillator and excites electrons in the material of the scintillator. These electrons quickly go back to a de-excited state by releasing a photon. The photon is then detected by a silicon photomultiplier (SiPM).

Construction

Building the Cosmic Watch is very simple, all the information needed to build the device can be found on the Cosmic Watch website and GitHub. The biggest challenge in building the device is obtaining the correct materials. In the case of the first Cosmic Watch built, various components were incorrect or different to the ones found in the purchase list. After obtaining all the materials, the step-by-step instructions were followed.

Firstly, a microcontroller, in this case an Arduino Nano, is used to control the device to detect the triggers received by the SiPM and output the information for analysis. The Arduino Nano must be set up by uploading code to it, the code is found on GitHub. After that, the main primary circuit board (PCB) must be soldered. The main PCB has 40 components that must be soldered making it the most difficult piece to build. The SD card and SiPM PCBs are soldered next. The SD card PCB is used to output data directly to an SD card. The SiPM PCB includes the circuit that connects the SiPM to the Arduino Nano. Finally, the plastic scintillator is put on top of the SiPM PCB and a reflective foil is wrapped around it. All the components are combined, and an aluminum protective case is added.

A completed Cosmic Watch (without the aluminum case) can be observed in **FIGURE 1 (a)** . The black box on top is the plastic scintillator wrapped on top of the SiPM PCB. The LED screen and light are used to show the when a muon is detected.

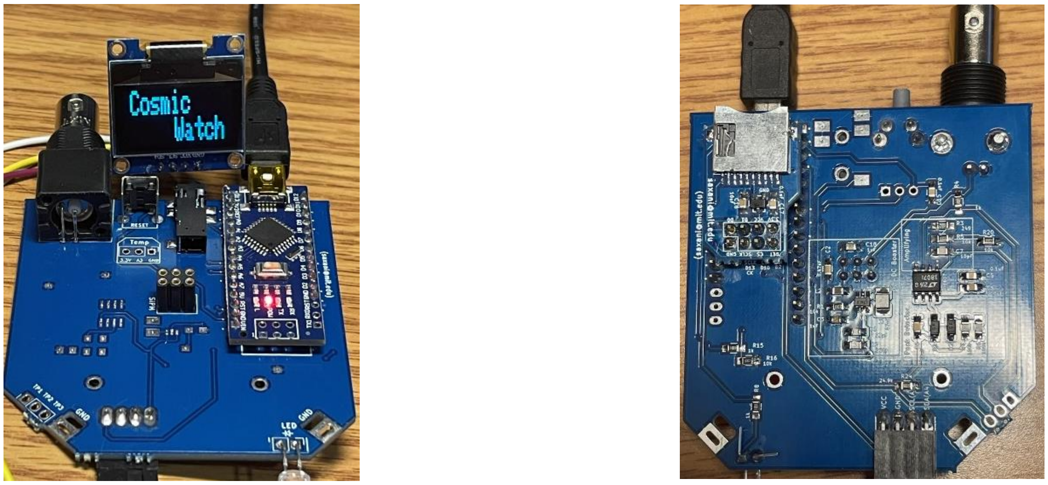


(a) (b)

FIGURE 1. Completed Cosmic Watch (a) before being put inside aluminum case and (b) after being put inside aluminum case. (Taken from the Cosmic Watch website[3])

Results

The detector build was not completed due to some problems with the SiPM and plastic scintillator. However, the main PCB was fully constructed, and the LED screen was working correctly. Unfortunately, because of this no data was taken by the Cosmic Watch. The built Cosmic Watch can be observed in **FIGURE 2**.



(a) (b)

FIGURE 2. Completed Cosmic Watch without the SiPM and Plastic Scintillator. Top (a) and bottom (b) of Cosmic Watch.

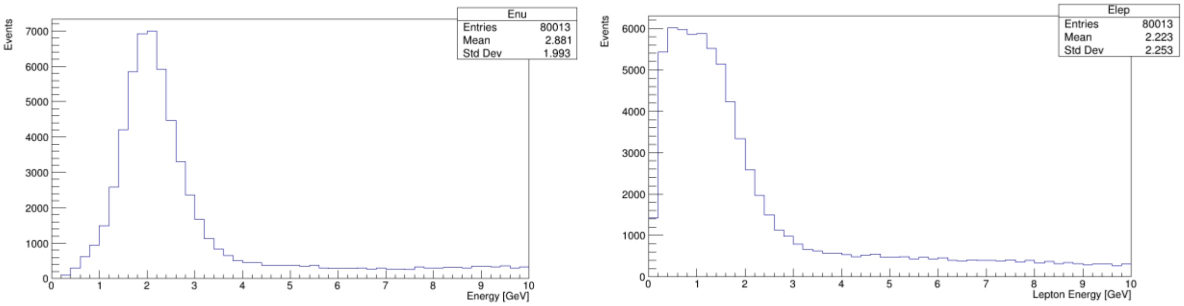
GENIE ANALYSIS

Simulations are an outstanding method of analyzing and better understanding neutrino cross sections. Finding accurate cross section models is important for improving current and future experiments. For neutrino interactions, an event generator called “Generates Events for Neutrino Interaction Experiments” (GENIE) is utilized. GENIE is an international collaboration developed by the best neutrino interaction experts in the world. GENIE is made up of around 110,000 lines of code and gives scientists the opportunity to change the custom model configuration (CMC) as they please. To analyze the data obtained from GENIE an object-oriented computer program called ROOT is used. ROOT was developed in C++ by CERN, and it is widely utilized for scientific analysis of large quantities of data, such as the ones found in particle physics.

Plotting

The first step of utilizing ROOT is learning how to use a terminal. ROOT is currently available in MacOS and Linux with a Windows version soon to come, however a WSL (Windows Subsystem for Linux) can be used to simulate a Linux terminal in a windows computer. Linux distributions like Ubuntu are utilized to acquire the Linux terminal. Once Ubuntu is installed, ROOT can be downloaded directly from the terminal following the instructions provided by CERN. To completely obtain all the features from ROOT, an X Windows System (X11) must also be downloaded to get a display. This is very helpful when analyzing graphs and writing code.

Now that ROOT is downloaded, files from GENIE can be plotted and analyzed by creating some code. These GENIE files come with “TTrees” inside which is what will be used to obtain the first histograms. TTrees are where the data from the GENIE simulation is stored, these are useful because each detected variable in the simulation is stored separately in “branches” which makes it easy to cut, combine and normalize the data. In the files used for this project the branches inside the TTrees had variables such as, *“Energy of Neutrino”*, *“Energy of Lepton”*, *“Transverse X/Y/Z Momentum”* , among others. Each of these variables come as histograms inside the TTree.



(a) (b)

FIGURE 3. Histograms depicting the Energy of Neutrino (a) and the Energy of the lepton (b) with respect to the number of events.

Besides these variables, there are also other characteristics that are used to differentiate different types of interactions. Things like, *“Neutrino Flavor”*, *“Charged or Neutral Current”* and *“Interaction Mode”* will be used to analyze the variables more in depth by constraining them to specific parameters.

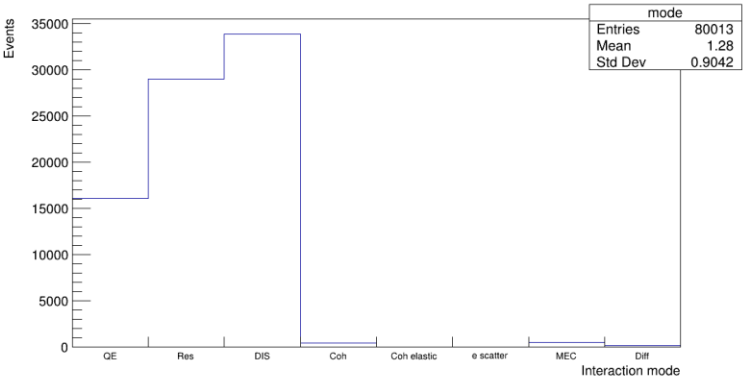


FIGURE 4. Histogram of Events vs Neutrino Interaction Mode

Now that all the variables are identified inside the TTree, as well as the different interactions modes, they can be combined to obtain the information needed for analysis. For example, **FIGURE 5** shows the energy of a muon neutrino in a quasi-elastic scattering with a charged current. It can be observed that most events happen at 2 GeV which is expected from previous simulation samples like the one in **FIGURE 3 (a)**.

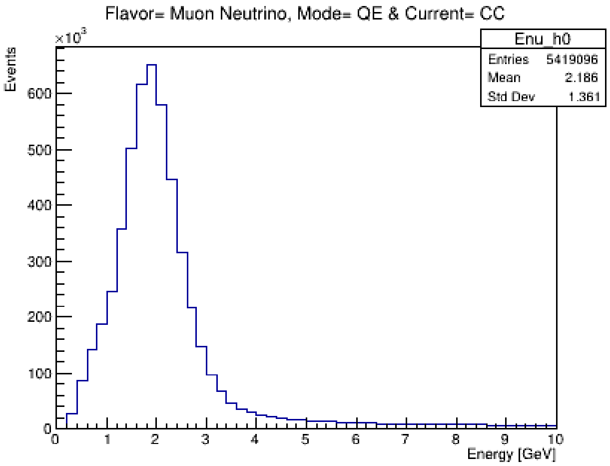


FIGURE 5. Histogram of energy of neutrino vs events in quasi-elastic charged interaction of a muon neutrino.

Now that specific simulation conditions can be graphed, it is time to compare different simulation files that utilize distinct custom model configurations. To do this, every combination of neutrino flavor, charge and interaction mode must be graphed with respect to each variable. There are four neutrino flavors in the simulation: muon neutrino, muon antineutrino, electron neutrino and electron antineutrino. For the analysis only four neutrino interaction modes are observed: QE (quasi-elastic scattering), DIS (deep inelastic scattering) , RES (resonant pion production) and MEC (meson exchange current). As explained before, there are two types of neutrino interactions: charged current and neutral current. In total, 16 combinations are obtained for the analysis. Considering there is 16 variables, it adds up to 256 plots per file.

After plotting all the graphs for each file, the files can be compared using a code that area normalizes the histograms and puts them in the same graph. An example of this can be seen in

FIGURE 5, where two files are being compared for the variable of neutrino energy in a quasi-elastic charged interaction of a muon neutrino. It can be observed how the two files differ from each other at every point.

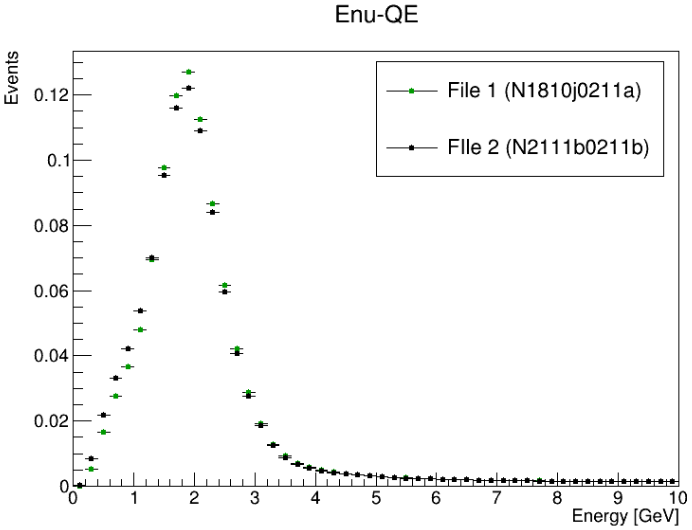


FIGURE 6. Comparison between two simulation files with different CMCs

Results

After the code was created to compare two different files, it was now time to do the same process but with more files this time. The files used for the result were six, five of them came from the new GENIE v3.2 version and one of the files (the old reference) came from the older GENIE v3.0.6 version. For this specific analysis, only the muon neutrino charged interactions were plotted. At the end 64 plots like the one shown in **FIGURE 7** were obtained.

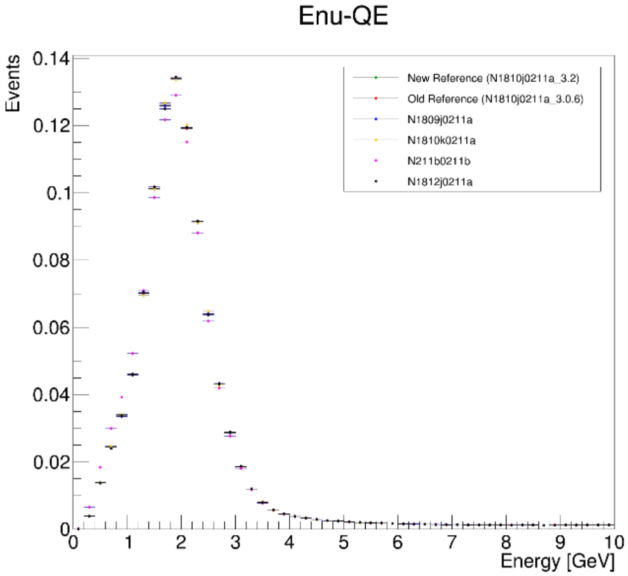


FIGURE 7. Comparison between six simulation files with different CMCs for neutrino energy.

Besides analyzing how different the files looked from each other in comparison plots, another method of analysis was also used to check how the files differed. This method was dividing each data point by the same point in a different file, therefore obtaining a ratio. For this, all the files were divided by the same file (new reference) and the results were plotted into the same graph. It can be observed that, for the example in **FIGURE 8**, the files are very similar as most points are near 1. Another 64 files were obtained from this for further analysis.

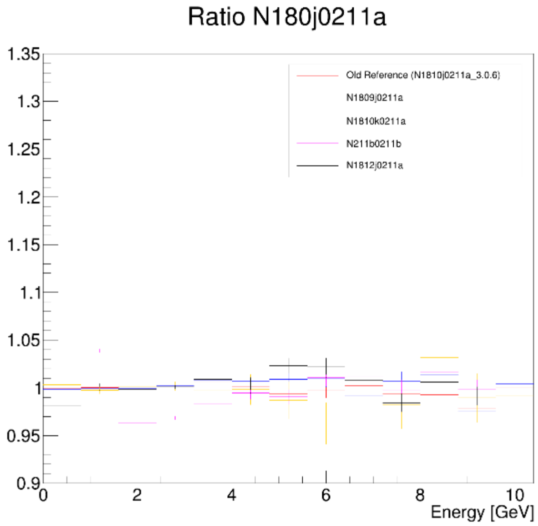


FIGURE 8. Ratio between all the files and the new reference for neutrino energy.

CONCLUSION

Building the Cosmic Watch was a very interesting and new experience. Unfortunately, not being able to complete the project was unexpected and displeasing. Hopefully soon the project can be completed before the MMBC is finished being built. Even though the project was not completed, the work done will set an example for future interns on how to build the Cosmic Watch and avoid the mistakes committed during this first-time learning experience.

On the other hand, the data analysis was fun but also frustrating at times. With no prior experience, it was not only difficult to code the plots in C++ but also to learn to use WSL and the Ubuntu terminal. It was rewarding obtaining the final graphs, however more work must be done to improve the code and analysis as well as work on different types of simulations. This project is a useful tool that can be expanded on for future use.

REFERENCES

[1] M. Bentancourt, Neutrino Cross Sections, 2016
[2] J. Bian, The NOνA experiment: overview and status, 2018
[3] Cosmic Watch. http://www.cosmicwatch.lns.mit.edu/, 2017