Summer Research Placement Report: Supernovae Neutrinos

Michael Soughton, ms731@sussex.ac.uk
Supervisor: Simon Peeters,
Working with: Michael Baird

21^{st} September, 2016

Abstract

The Deep Underground Neutrino Experiment (DUNE), which is part of the The Long-Baseline Neutrino Facility (LBNF) currently under construction, aims to provide new information regarding the production of neutrinos inside supernovae. First, a reliable trigger for supernovae neutrinos must be made so that the full data-readout of a supernovae can be saved (full data steam is normally discarded). This project looked into obtaining useful Monte Carlo truth information of supernovae neutrinos which could be compared to background noise in order to produce a trigger. Useful truth information was obtained which revealed a flaw in the simulation of the detector geometry which will be resolved. Now steps can be taken with the information to produce a trigger.

Introduction

During the last decade, the neutrino community has made efforts to construct a new generation of neutrino detectors. The Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE), due to be constructed in the next decade, will aim to have a 1.2 MW neutrino beam at Fermilab by 2026 which will be upgraded to 2.4 MW by 2030. A near detector will detect neutrinos from the beam near it's source and the DUNE far detector will detect beam neutrinos and supernova neutrinos as well as other background neutrinos eight-hundred miles away and will consist of four 10 kt Liquid Argon Time Projection Chamber (LArTPC) modules located deep underground. DUNE will search for CP-violation in neutrino oscillations, determine the ordering of the neutrino masses, test the three-neutrino paradigm, search from proton decay if it exits and will provide new information on how supernovae explode [1] and what new physics can be learnt from a supernova neutrino burst - there has only been one recorded supernova neutrino event. DUNE should be able to determine the time, flavour and energy structure of a neutrino burst, however in order to retrieve useful data from a neutrino burst, we must develop software which will reduce the data readout (4.6 Tb s^{-1} for four 10 kt LArTPCs) to something more manageable. My project looked at investigating the properties of neutrinos from a supernova neutrino burst and what we will need to know to be able to trigger a supernova neutrino readout to aquire useful data should one occur.

Getting setup at Fermilab and started with ROOT

The majority of my work on this project would be done on the Fermilab servers, thus I would need a Fermilab account. I had already set-up my account following the instructions at `https://web.fnal.gov/collaboration/DUNE/SitePages/Getting%20Computer%20Accounts%20at%20Fermilab.aspx`. This provided me with my own directory on the Fermilab servers and the ability to access them. Fermilab uses Kerberos for strong authentication - I was provided with a kerberos pricipal and password which I kept safe. I would use this to login to the servers with the use of kinit. For example to connect to the first DUNE server, I would use `'kinit -fl 7d soughton@FNAL.GOV'` and then enter my kerberos password, after which I could connect to the server with
`'ssh -YK soughton@dunegpvm01.fnal.gov'`.

I would be using ROOT to plot histograms throughout my project. ROOT is an object oriented framework for large scale data analysis, which utilises C++. To set up ROOT to work on the Fermilab servers I would have to build and then source DUNE and LArSOFT (LArSOFT is a collaboration of software used for LArTPCs). One can build a release of LArSOFT by following the instructions at `https://cdcvs.fnal.gov/redmine/projects/35ton/wiki/Getting_Started_Examples`, remembering to move to the feauture branch to be used (here 'feature/mbaird42/SupernovaAna') using `git checkout`. I added some start-up scripts which will source DUNE and LArSOFT and set other useful shell variables. These can can be seen in my home directory `'/dune/app/users/soughton'`. One may have to occasionally rebuild their LArSOFT release with a newer version following the same steps.

Supernovae Neutrinos, Liquid Argon Time Proportion Chambers (LArTPCs) and Monte Carlo (MC) Simulations

Since my project would look into the detection of supernovae neutrinos, an understanding of the origin of these neutrinos and how they will be detected was required. Supernovae produce a very large number of neutrinos - around 99% of their gravitational binding energy is converted into neutrinos. Supernovae are of two main types, type I and type II, each with sub-categories. Type I supernovae occur when a white dwarf - a lower mass star in its final evolutionary stage, which is prevented from collapsing from the pressure of electron degeneracy, accretes enough matter from another nearby star that the star becomes massive enough that it is favourable (it requires less energy) for electrons to be captured by protons that it does to fill electron states (electrons follow Fermi-Dirac statistics) and so neutrinos and neutrons are produced by electron capture as

$$e^- + p \rightarrow \nu_e + n$$

and the star starts to collapse until collapse is halted by stronger neutron degeneracy. The mass at which a white dwarf will collapse is always 1.44 Solar Masses (the Chandreska Limit). Type II supernovae occur when a supermassive star has reached the point in it's lifetime when it has converted a significant amount of its matter into heavier elements. Fusing elements heavier than iron is an endothermic process, so the star does not produce enough energy in the core to prevent collapse. In both cases, as the star undergoes core collapse, there are a large number of electrons and protons with enough energy to undergo inverse beta-decay/electron capture. This phase lasts for about 10 ms [2]. As there is so much in-falling matter, many of the neutrinos interact with it, even though neutrinos interact so rarely. The neutrinos that escape can be seen as an initial neutrino burst, which is when the detector must trigger a supernova. Most electron flavours are of electron neutrino, then of anti electron neutrino with few (anti) muon and tau neutrinos.

It is thought that the interaction of these neutrinos with the in-falling matter is enough to prevent all the matter from falling into a black hole and to launch the matter outwards. After the accretion phase, there is the cooling phase as the clouds of matter expand outwards. We still see neutrinos on the order of 10 s, but the luminosity of all flavours will gradually decline. There will be minimal neutrino oscillations in the vacuum of space, although if the supernova occurs on the other side of the Earth to the detector, then there will be neutrino oscillations due to the Earth. The oscillations through the Earth are fairly well known down to a certain depth, although oscillations through the center will introduce uncertainty unless there is a detector on the other side of the Earth to give un-shifted results.

A LArTCP is a large chamber mostly filled with Argon-40. Electron neutrinos will interact with the Argon-40 through inverse beta decay through the interaction

$$\nu_e + {}^{40}\text{Ar} \to e^- + {}^{40}\text{K}^* + m\gamma$$

where and m is a positive integer (usually less than or equal to three). Similarly, anti neutrinos interact through

$$\bar{\nu_e} + {}^{40}\text{Ar} \to e^+ + {}^{40}\text{Cl}^* + m\gamma$$

LArTPCs only interact with supernova muon and tau neutrinos through NC (Neutral Current - a neutral Z Boson mediates the interaction between neutrino and electron scattering)interactions as they do not have enough energy to produce a muon or a tau electron unlike the beam muon (and anti) neutrinos which have much more energy and so can interact through CC (Charged Current - a charged W^+ or W^- Boson mediates a neutrino going to a lepton and a lepton going to a neutrino simultaneously) interactions.

The produced lepton travels off some trajectory with a high momentum, meaning that it ionises more Argon-40 along the way. An electric field (of strength 500 Vcm^{-1}) is applied across the TPC by an Anode Plane Assembly (APA) at one end and a cathode plane at the other [3]. The ionised Argon will move towards the cathode plane and the electrons towards to APA. The APA consists of three planes of wires as shown in Figure 1. The U and V planes consist of induction wires which see a bipolar signal as an electron passes by. The Y plane consists of collection wires which see a unipolar signal as the electrons are collected on it. These three readings can be combined to determine the trajectory of the lepton and it's properties such as energy and momentum which can tell us about the neutrinos. However we must also know the time at which the interaction happens. The produced photons may move off to hit a photodetector, but there are not enough of them to signal that they were the products of the interaction. Fortunately, Liquid Argon is a good scintillator - the electrons from ionisation can recombine with an Argon nucleus which can then briefly bond with another before decaying, releasing more photons. Enough photons are released to give a time for the interaction. Acrylic bars coated with Tetra-N-phenylbenzidine (TPB) or doped in bulk will be installed in the APA frame. Signals are then read out electronically to be used as a trigger for the interaction time in the Data Acquisition (DAQ). TPCs will be stacked back to back so that their APAs overlap. This will improve the chances of pile-up, where a large number of interactions occur within one event and physically close to each other in the detector meaning that there is an ambiguity to which interaction occurs before another one, but makes the construction more cost effective.

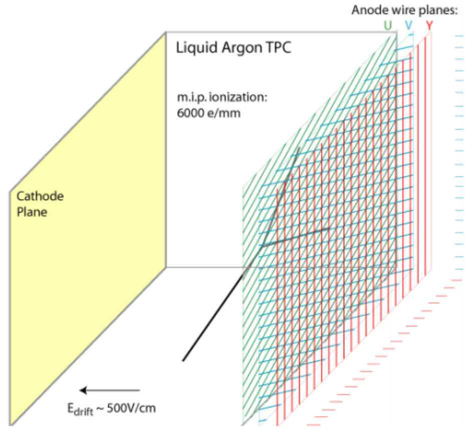

Figure 1: Figure showing the TPC and APA design. [4]

The amount of neutrinos detected will depend on the supernovae type and distance from Earth. For a core-collapse event 10 kPc away from Earth, there will be of the order of a few hundred interactions per event (the smallest unit of time measured by the DAQ, which is 0.5 µs) during the initial burst. This is orders of magnitude greater than the number of interactions from background sources, so would be immediately apparent when the DAQ is viewed. However the DAQ receives about 40 Tbs^{-1} of data which must be overwritten shortly after, meaning that important data such as a supernovae readout must be saved to memory. This is why we must construct a trigger which will know when a supernovae occurs and save the readout. To build this trigger, we must have information on some of the properties of supernovae neutrinos to be able to distinguish them from the background such as the number of interactions, their energy, momentum and many other properties of the interaction. Since real data will not be collected for a number of years, Monte Carlo (MC) simulations are used. MC simulations are a set of computational algorithms which give numerical results based on random sampling about a probability distribution. For example, say we expect the number of neutrino interactions (which we can call the number of MC truths - named truths since the simulation, these 'truths' are what are 'actually' happening) per event from a supernovae to be distributed according to a Poisson distribution.

Finding MC truths and hits from an event

I would need to be able to analyse truth information about neutrinos. To do this I would be running a supernova neutrino analysis module over neutrino truth files. This module can be found at
`'dune/app/users/soughton/larsoft_v06_02_00/srcs/dunetpc/dune/SupernovaAna/SupernovaAna_module.cc'`
The module gets truth and hit information from the event and then can fill histograms or an N-Tuple. Note the version filling only histograms can be found in the same directory. The modules uses ART and LArSOFT to get and uses truth data. One can follow how the module does this at `https://cdcvs.fnal.gov/redmine/projects/novaart/wiki/Using_the_Framework` and can follow the documentation on how to use specific classes at `http://nusoft.fnal.gov/larsoft/doxsvn/html/namespaceart.html`. The module initially would only get the number of MC truths per event. This would be useful as we should get multiple truths per event for a supernova burst, with the distribution being Poisson. However, we initially did not have any supernova files to run this module over, so I would run the module over a Genie file (for beam neutrinos). This file had set the number of MC truths per event to be one for all events, but the file would suffice for the time that I would learn how to get MC data from a file. In the meantime Michael was working on producing a supernova file. I added to the module, histograms and N-Tuple branches containing information on the origin source of a neutrino (beam, solar, supernova or otherwise), whether it's interaction was Charged Current or Neutral Current and the angle between the incoming neutrino and outgoing lepton.

The problem of pile-up would be a big hindrance in determining the properties of neutrinos. We wanted to investigate if the primary lepton were to hit the APA, would its summed ADC (Analogue to Digital Current - the product of the charge deposited by the lepton and the time for which it deposits charge) have some dependence on the angle at which it hits. We would expect summed ADC to be greater if the lepton is travelling more along the axis of the wires and to also have a dependence on the lepton velocity according to the Betha-Bloche curve. Knowing the angle of the lepton could help determine it's source of origin (where the interaction occurred) and thus solve eliminate some pile-up. I then added momentum truth information so as to determine the angle through trigonometry. A plot of detector angle against summed ADC can be in Figure 2. Also a related plot is the detector angle against number of detector hits also in Figure 2. When writing in C++, one has to be careful when using arrays to take precautions not to end up attempting to add entries to an array whose length is not long enough or else there will be a segmentation fault. My code contains an if statement to avoid this. By the time I had finished adding this to my code, Michael had prepared some new files for supernova neutrinos, one containing only one neutrino per event and one containing a mean of twenty neutrinos per event, Poissonly distributed. I would make a few histograms of these files, including, for the file with one neutrino per event, number of (detector) hits against neutrino energy, summed ADC against neutrino energy, the angle and which the lepton travels towards the detector against number of hits and a histogram of electron energy. For the file with (a mean of) twenty neutrinos per event, I would make histograms of number of hits against number of MC truths, summed ADC against number of MC truths and of electron energy. I learnt how to make plots in ROOT using a C++ macro (can be seen in my home directory).

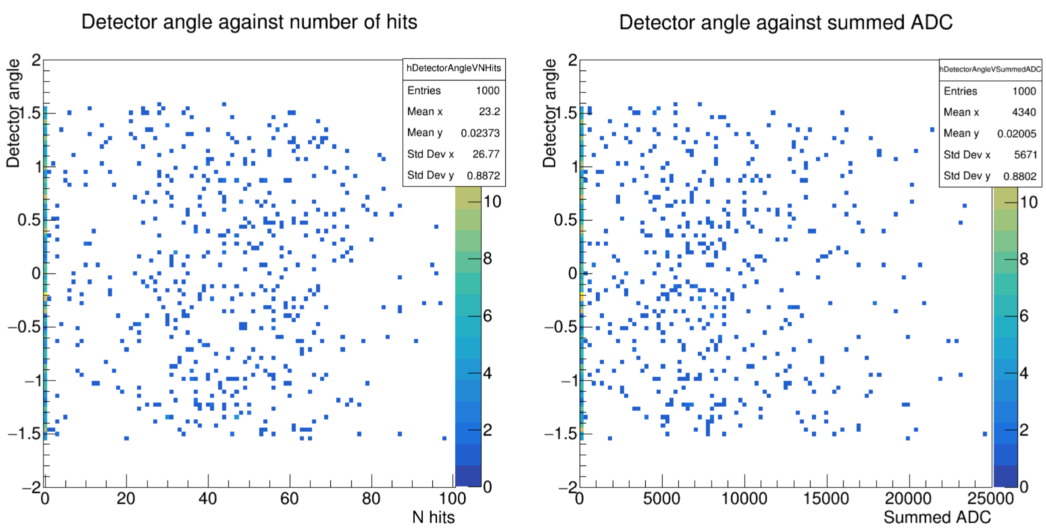

Figure 2: HIstogram of detector angle against number of hits and agaisnt summed ADC.

Finding hit problems

From the plots of detector angle vs number of hits and of detector angle vs summed ADC, for the file with only one neutrino, it was apparent that there were some events for which no hits or ADC was recorded, although all the other truth information was properly loaded. This implied that the simulation was failing to simulate events correctly the detector geometry. We initially wanted to see if electrons could be hitting the APA frame so would not count as a hit or give any ADC signal. To investigate this, I added the initial x,y,z and t information for the electrons (there would be negligible drift) and made plots of the vertices FIG. If electrons were hitting the frame, then with a cut for number of hits equal to zero, would just show the where electrons had hit the frame. This was not the case however, the hits still appeared randomly distributed with the cut. Michael produced some more supernova file, containing a larger number of events. These files had the same problem of getting zero hits or summed ADC. I had to update my release of LArSOFT following the steps as before and change some of my header files to match during this time as the new files depended upon the new release. I constructed numerous plots in attempt to uncover why this problem was occurring. A plot of the number of particles involved in the interaction (normally an electron neutrino, and electron and a few photons) against time revealled that some particles around $t = 0$ did not have any hits. A plot of x (the electrons drift in the x direction towards the APA) against t shown in Figure 3 revealed why. About half the events occurred too far away and too late for the electrons to drift to the APA by the end of the simulation window. This demonstrated a problem with the simulation times, not with the physics involved and could be rectified by stopping events at a certain time and keeping the simulation running for long enough for the electron to reach the APA, although this would require more CPU, it should not be a problem for actual data as the readout is continuous. Still, this had uncovered a problem which would be a major hindrance in using MC data to build a working supernova trigger. With this solved and all the MC data, we can now look into building the trigger, which will need to compare the properties of a supernova burst to the background and determine when to start saving data. This will take time but is now achievable.

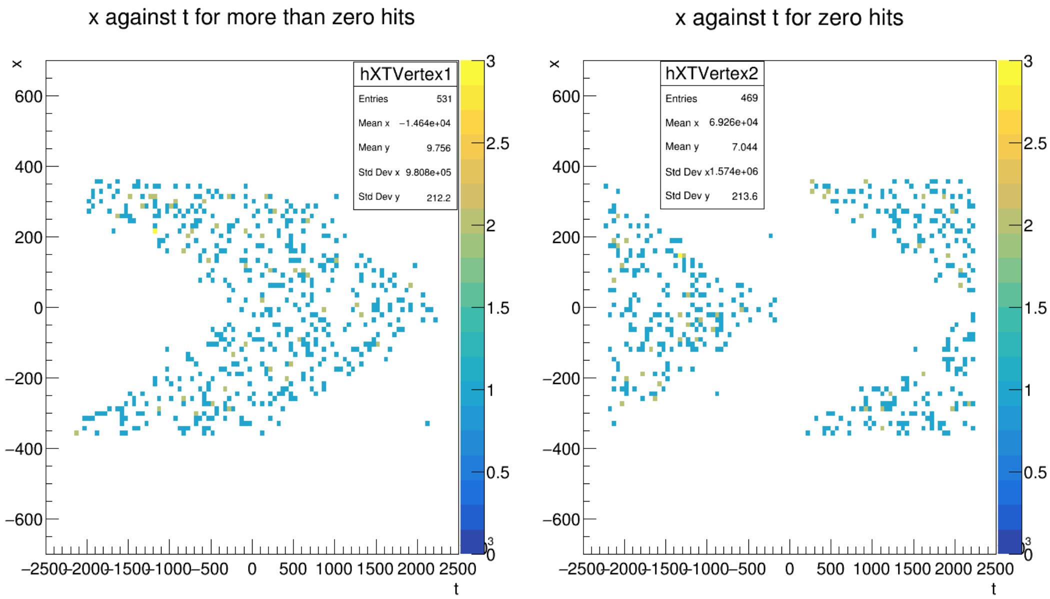

Figure 3: Histogram of initial x position against initial t of electrons with cuts.

Summary

During my project I familiarised myself with the programs and software I would be using. This took some time but I was able to make progress whilst learning at the same time. I also had to read-up on Liquid Argon detectors and supernovae neutrinos. I managed to write code in C++ which would get useful Monte Carlo truth and hit information about a neutrino interaction and produce histograms with the information which will be useful in distinguishing the difference between supernovae neutrinos and background noise. The reason for an absence of electron hits was discovered to be due to an error in the detector geometry and event timing, which will be resolved in the future. The next step will be to compare the truth information from the supernovae neutrinos to that of other neutrinos and of electrons produced by the decay Argon-39 inside the chamber. Doing so should allow us to produce a reliable trigger for supernovae neutrinos.

My Experiences

I thoroughly enjoyed working on this project. My understanding of particle physics and of how experiments work has improved greatly. I have also gained experience of working with C++, ROOT, LArSOFT and ART and of being in a real research group. I found the project to be challenging, but I liked that aspect as I was able to solve problems that I would not have otherwise faced during my studies.

Biography

I have just completed my second year at Sussex, on the MPhys with Research Placement course. In the future, I would like to obtain a PhD and pursue a career in research. My areas of interest within physics are quite broad at the moment, so I am not yet certain which field I would like to enter, although I am very interested in particle physics and I am considering it an area I would like to work in for a PhD.

A final note

I have found my Research Placement to be very rewarding and valuable to me. As well as developing programming skills and a deeper understanding of particle physics, I have also learnt what it would be like to work in a research team. I would recommend the Research Placement to anybody else.

Bibliography

[1] R. Acciarri *et at.* (2016), *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)*. arXiv:1601.05471

[2] K.Scholberg (2012), *Supernova Neutrino Detection*. Department of Physics, Duke University, Durham NC 27708, USA,

[3] R. Acciarri *et at.* (2016), *Annex 4A: The LBNE Design for a Deep Underground Single-Phase Liquid Argon TPC*. arXiv:1601.02984

[4] B.Viren, *Wire Cell Event Reconstruction Software for LArTPC Detectors*. PowerPoint Presentation, Department of Physics, Brookhaven National Laboratory, 2015