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Introduction

Since the discovery of neutrino flavour oscillations, which implies that neutrinos have mass, neutrino physics has enjoyed a period of rapid development. The field has begun to transition into an era of precision, with many of the parameters governing these oscillations having been well constrained. The fact that neutrinos have mass, and the success of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) theory in describing neutrino oscillations, leads to a number of fundamental questions which have important implications for both particle physics and cosmology:

- What is the mechanism giving rise to neutrino mass?
- Are neutrinos Dirac or Majorana particles?
- What is the absolute scale and ordering of the neutrino masses?
- Do neutrinos and anti–neutrinos oscillate differently, and would this help to explain the matter anti–matter asymmetry in the universe?
- Are there any sterile neutrinos?

The high resolution and large masses of modern neutrino detectors also make them useful tools for both astronomy and astrophysics. 2017 has widely been considered as the dawn of multi–messenger astronomy, with a measurement of gravitational waves at the Laser Interferometer Gravitational–Wave Observatory (LIGO) being correlated with measurements of a neutron star merger from electromagnetic telescopes[1]. This measurement was shortly followed by a similar correlation, but in the neutrino sector, between a high energy neutrino event in the IceCube Neutrino Observatory and a number of traditional telescopes[2]. Within our galaxy, neutrino detectors provide a unique opportunity to understand the underlying mechanisms in supernovae; in the case of such a supernova, the structure of the neutrino flux at earth provides a mechanism to measure effects in the early stages of the supernova burst, which are inaccessible with electromagnetic measurements[3].

Each of these questions places unique constraints on the design of an appropriate neutrino detector. The discovery of a matter anti–matter asymmetry in neutrino oscillations could be answered by making precise measurements of neutrino oscillations. This requires reliably identifying the flavour and energy of neutrinos in order to measure the appearance and disappearance spectra associated with neutrinos produced in long baseline neutrino experiments. To identify the low energy electrons produced in supernova neutrino interactions, a detector with low thresholds and low backgrounds is required. The Deep Underground Neutrino Experiment (DUNE) aims to tackle these challenges by utilising the liquid argon time projection chamber (LArTPC) technology, whose high spatial and calorimetric resolution allows for more accurate geometric classification of neutrino interactions. To achieve these goals, a significant programme of LArTPC research is ongoing with construction, reconstruction, and analysis methods all under development in a number of LArTPC based experiments[4–7].

This thesis presents analyses of charged particle interactions in the ProtoDUNE–SP LArTPC detector, using data collected during with a test beam between August and November 2018. Hit classification and Michel electron reconstruction are investigated, and a sample of Michel electrons is used to provide a measurement of the energy resolution and bias for low energy electrons in ProtoDUNE–SP.

Particle classification plays an important role in event reconstruction in LArTPC detectors. In particular, the clustering of hits into tracks and showers is an important step in reconstructing events in a LArTPC. After tracks and showers have been reconstructed, they can be combined to build up a picture of the full particle interaction. This thesis presents the results of the development of a hit classification algorithm based on convolutional neural networks. The primary goal of this algorithm is to classify hits as track–like or shower–like on a hit–by–hit basis. The output from the hit classification has been applied to analyses of beam particle interactions, such as pion cross–section analyses, and cosmic–ray interactions, which are used to calibrate the ProtoDUNE–SP detector. These outputs are also used to select a sample of Michel electron candidates, which are analysed in this thesis.

Michel electrons have an energy spectrum spanning 0–60 MeV. Understanding electrons in this energy range is important, as they have a similar energy to the electrons produced when neutrinos from supernova bursts interact. In a LArTPC, at these energies, the energy deposition of electrons transitions between ionisation dominated and radiation dominated regimes, making for a unique event signature. The work presented in this thesis also details the selection and reconstruction of Michel electron events in ProtoDUNE–SP, based on machine learning algorithms. Analysis of the reconstructed Michel electron events is used to quantify the energy resolution and bias for low energy electrons in ProtoDUNE–SP based on this approach. The results of this analysis provide valuable inputs to studies of supernova burst neutrinos in LArTPC detectors.

In this thesis, chapter 2 provides a theoretical overview of neutrinos within the standard model. Interactions, oscillations, and production will be discussed summarising the current knowledge in this field, as well as open questions which will be studied in ongoing and upcoming experiments. The role of neutrinos in supernova bursts and the detection of such neutrinos in a LArTPC detector will also be discussed in more detail.

The ProtoDUNE–SP experiment is described in Chapter 3, including details of the beam line, detector, cosmic–ray flux, and simulations. An overview of the

LArTPC detection principle will be given with specific details of the ProtoDUNE–SP design. Some details of detector operations will be discussed, paying particular attention to the monitoring of the detector via the online data quality monitoring system, which has been the author's major contribution to the detector operations.

Chapter 4 will cover details of electromagnetic energy loss in liquid argon. Electron and photon energy loss will be discussed as well as processes leading to electron-ion recombination. The impacts of these effects on electron reconstruction in liquid argon will be highlighted.

The main analyses of this thesis, which are discussed in Chapters 6 and 7, make use of neural network algorithms for reconstruction, therefore, Chapter 5 will briefly outline the relevant details of these algorithms.

Chapter 6 will detail the development of a hit classification algorithm based on convolutional neural networks. This algorithm is used to classify hits as track–like or shower–like in ProtoDUNE–SP, as well as to identify Michel electron hits. The results of this algorithm are being used in a number of analyses of ProtoDUNE–SP data, including the selection of Michel electron events, which is discussed in Chapter 7.

In Chapter 7, Michel electron reconstruction in ProtoDUNE–SP will be discussed. First, a brief overview of Michel electron production and energy loss in liquid argon will be given. This will be followed by a discussion of the event selection and energy reconstruction algorithms, which were developed to study Michel electron events in ProtoDUNE–SP. The reconstructed Michel electron spectrum will be compared between data and simulation, and the energy resolution and bias for low energy electrons in the ProtoDUNE–SP detector will be estimated. Finally, the results will be compared to those from similar experiments, and their implications for DUNE will be highlighted.

A summary of the results will be given in Chapter 8 along with a discussion of the implications of these results for physics in LArTPC detectors.