A preliminary investigation into determining CC0π cross-section sensitivities in SBND and performing a GENIE global fit to neutrino scattering data

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1st year PhD report

Abstract

Random stuff

1. Introduction

Neutrino physics is at the core of current high energy research. One of the profound discoveries made in recent years was the observation of neutrino flavour oscillations by the Super-Kamiokande (Super-K) experiment, which was the first confirmation that physics existed beyond the standard model of particle physics. In brief, neutrinos described by the standard model would be massless particles, but since the flavours are made up of superpositions of mass states, the oscillation of the flavour states implies that the relative mass states are different, and therefore non-zero [1].

Future, long-baseline, neutrino experiments such as the Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (Hyper-K) are hoping to investigate some of the most fundamental questions we are still asking: Why does the universe constist of matter, and not anti-matter? What is the neutrino mass heirarchy? Neutrino research is an extremely active field. Optimising the current and future detectors to maximise the accuracy of all interaction anaylses is a crucial step towards obtaining concrete answers to these questions.

A brief introduction to the topics covered in this report is as follows, more detail on each will be given in later sections.

1.1. Neutrino interactions

Due to the elusive nature of the neutrino, directly observing one in a detector isn't possible. It is therefore necessary to infer their existence from particles produced when they interact. Since this process relies upon the reconstruction capability of the experiment, purpose-built detectors will attempt to maximise the efficiency of this.

Another property of the neutrino which poses a significant difficulty within detectors is their interaction probability, or cross-section. A typical neutrino cross-section is on the order of 10^{-44} cm^2 which corresponds to $\sim$1 interaction every 10 light years in steel, for neutrinos with only a few MeV energy [2]. This fact introduces the need for the interacting neutrinos to have high energies in these dedicated experiments, if we are to sufficiently reduce their mean free path. More detail on this topic will be discussed in section 3.

1.2. Cross-sections

In order to correctly model neutrino events within a specific detector geometry and material, certain parameters have to be known. In particular, the probability of an interaction taking place - its cross-section - is required for each possible interaction the neutrino could undergo. Cross-section measurements are therefore a necessity for the Monte Carlo event generators, and consequently the future detector studies mentioned earlier.

The extent of our current knowledge of charged current neutrino cross sections is shown in Figure 1. The plot contains cross-section information from multiple types of neutrino experiment, differing in both target material and detector machinery. A feature of this plot which is of the most interest to a Short Baseline Near Detector (SBND) cross-section study in particular, is the lack of precision in the measurements made towards the ∼1 GeV region [3]. SBND will not only be operational at this energy range, but it will also have statistics substantial enough to potentially make a significant contribution to improving the current knowledge in this region.

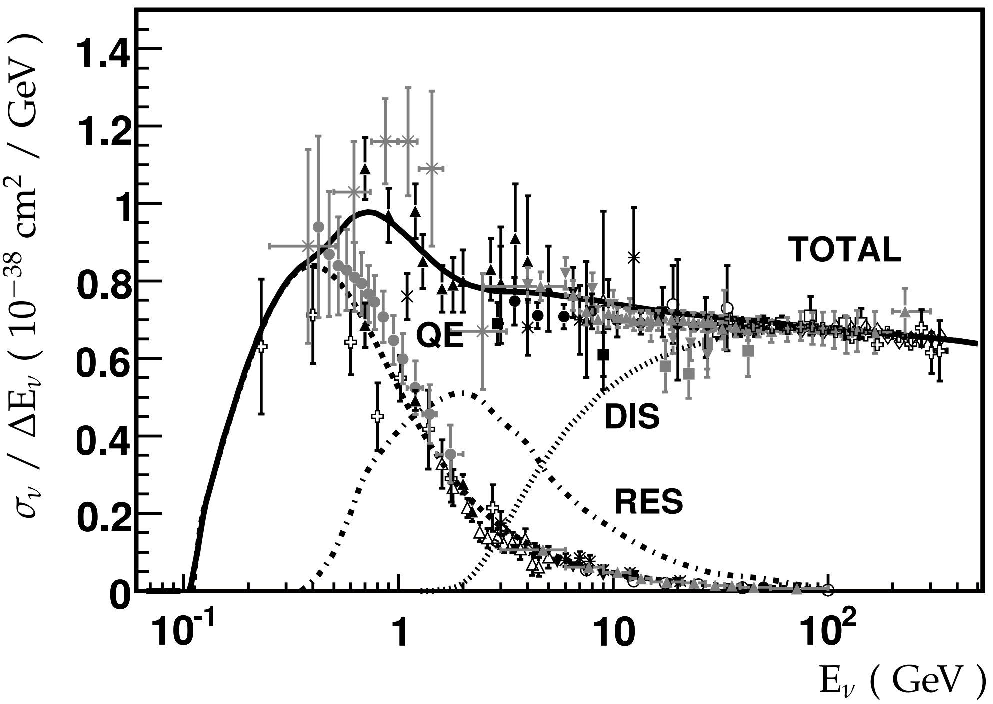

Figure 1: *A compilation of the total cross-section data across the ∼1 MeV to ∼100 GeV energy range. Including a breakdown in terms of the quasi-elastic, QE, resonant, RES and deep inelastic scattering, DIS, topologies [3].*

The scale of contribution SBND could make to this area of physics would in turn improve the predictions made by event generators for the next generation of neutrino experiments. Cross-sections will be discussed further in section 4.

1.3. GENIE and the GENIE-Professor global fits

GENIE is the world leading Monte Carlo neutrino interaction generator. Generators are a crucial machinery in all high energy physics analyses as they use theoretical models to produce predictions of how and where neutrino interactions will occur in specific detector geometries [4]. With this information, comparisons between experimental data and theoretical predictions can be drawn, the models can be updated and potential new physics can be explored.

Generators such as GENIE bridge the gap between theory and experiment, whilst also providing opportunities to prepare simulations and perform sensitivity studies for the next generation of neutrino experiments.

Alongside building state-of-the art detectors and making high precision cross-section measurements to improve current and future neutrino physics analyses, the predictions made by the generators can be improved by taking existing neutrino data and performing a fit of the models to them.

An effort to do this is currently being carried out by GENIE, using the Professor software framework, which was written with this purpose for experiments at the LHC [5]. The ultimate goal of this exercise is to perfom a global fit to all neutrino scattering data and consequently produce comprehensive model configurations to further optimise the predictions made for the next generation of neutrino experiments. This work and GENIE's role in current and future neutrino experiments will be discussed further in section 5.

1.4. SBND Physics Goals

SBND is one of 3 liquid argon detectors using the same neutrino beam in the Short Baseline Neutrino (SBN) program. Together, they aim to explore neutrino oscillations at 3 different positions along the beam, allowing for highly senstive measurements to be made [6].

Another objective of the SBN program, along with many other neutrino physics experiments, is to observe or reject the existence of sterile neutrinos. Though this will not be discussed here.

The MiniBooNE and LSND experiments observed an excess of low energy electron neutrino appearance in their data [7]. One of the main physics goals of SBND is to look for and characterise this excess, in collaboration with any results obtained by the MicroBooNE experiment before SBND is taking data. The beamline of MicroBooNE is 470m compared to 110m for SBND, whether one or both experiments observe the excess will tell us if there was a dependence on the distance travelled by the neutrinos [6].

This report will further describe the current status of neutrino cross-section analyses, the level importance that these measurements have in the field, and how a sensitivity calculation in the low GeV energy region is being carried out. It will then explain in more detail how Monte Carlo neutrino generators can be, and are being improved using recent and historical scattering data, through a global fit of comprehensive theoretical model configurations.

2. Detector functionality and features of the experiment

2.1. Booster neutrino beam, BNB

A Booster Neutrino Beam (BNB) of muon neutrinos is formed by firing protons, taken from an accelerator with ∼8 GeV kintetic energy, at a beryllium target which produces a hadronic beam consisting mainly of pions. The pions in this beam are then focussed and polarised before they decay, mostly to muon neutrinos, which propagate into the TPC where they interact with the target material. The beam's high muon neutrino excess occurs because the dominant decay channel of pions is (1) [6],

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \tag{1}$$

and the branching ratio of pions decaying to electrons over muons on the order of $\sim 10^{-4}$ due to the relation given in equation (2) [8].

$$R_\pi = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 10^{-4} \tag{2}$$

The beam fires neutrinos directly into the time projection chamber (TPC) of an experiment at such velocities that it can always be assumed that the particles entered the TPC from one direction and, before iteracting, were forward-going. This technicality gives an immediate criteria for the removal of backgrounds, such as cosmogenic neutrinos, which would enter the TPC from all directions [6].

2.2. Liquid argon time projection chambers, LArTPC

In current and future neutrino experiments such as DUNE and the short baseline neutrino (SBN) program (SBND, MicroBooNE and ICARUS), liquid argon is the target material of the detector. Argon in this form is used due to its stability and purity as a noble gas, its high denisty and its low cost. These properties lead to resolution capabilities on the order of the Bubble Chamber experiments, which allows for high certainty in distinguishing between interactions and ultimately optimises the resolving power of the experiment [9]. An example event display in liquid argon from the MicroBooNE experiment is given in Figure 2 [10].

Once the neutrino has entered the TPC it interacts with an argon atom to produce final state particles in the detector. These particles may then decay, be asorbed or interact with the argon in the TPC. Ionazation electrons and photons are also produced through these interactions.

A general purpose LArTPC diagram is given in Figure 3. A brief description of its functionality is as follows [11]:

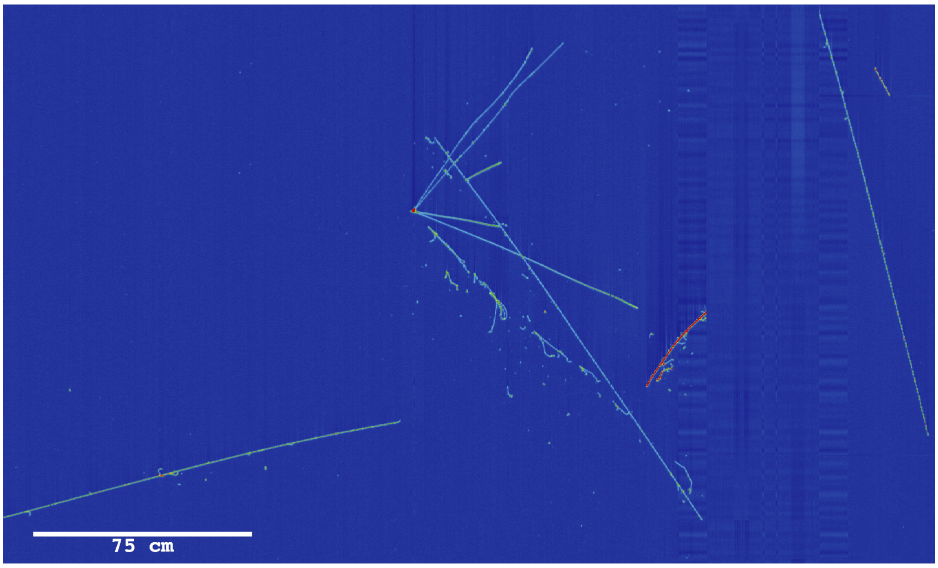

Figure 2: *An example event display from the MicroBooNE detector, one of the first to be seen in a liquid argon TPC. The resolving power is high enough for the tracks and showers to be clearly distinguished, along with the interaction vertex of the event [10].*

- A potential difference is induced between the cathode and anode planes
  - Electric field is induced by the potential difference
  - Ionization eletrons are caused to drift towards the three planes of wires on the opposite, anode side of the TPC
- Electron hits on the wires are converted to a current read out
  - Timing and spatial information deduced about the event
- Induction wire planes, U & V are situated at 60° to the vertical collection plane, Y
  - Full 3 dimensional read out is possible
  - Spatial information gives the y & z co-ordinates
  - Timing information determines the x co-ordinate
- Photons cascade into showers and reach the wall of PMTs residing behind the wire planes
  - Prompt scintillation light hits the PMTs
  - Provides additional information about the x co-ordinate of the event

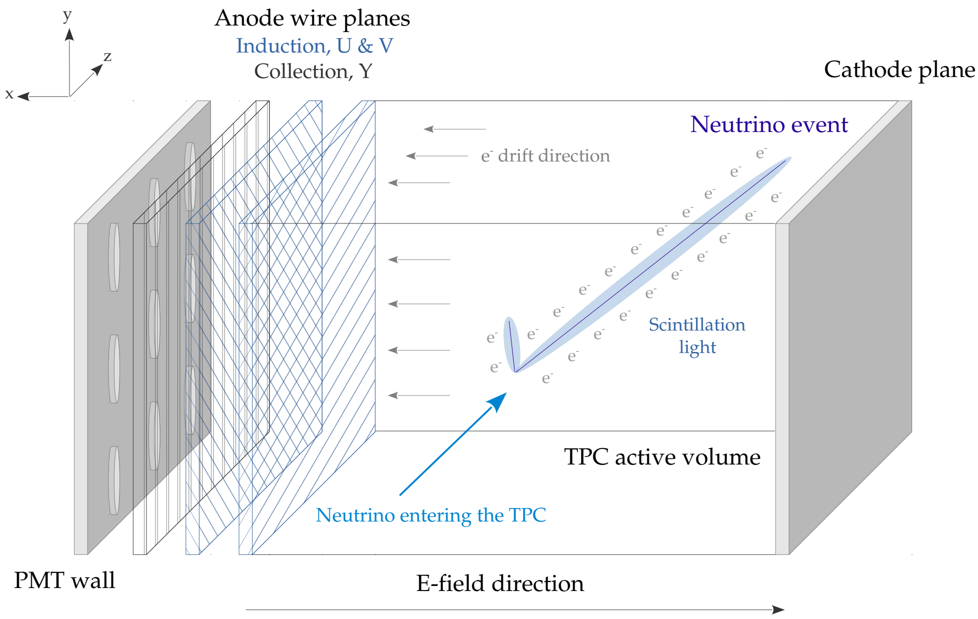

Figure 3: *An example neutrino interaction within a typical LArTPC. The ionization electrons drift in what is defined as the positive x-direction as shown, and the scintillation light would be collected by the wall of PMTs behind the wire places. The induction planes U and V are at 60° to the vertical collection plane Y. The neutrino would enter the TPC in the positive z-direction.*

2.3. SBND

SBND will have a beamline of 110m, the shortest in the SBN program. At this distance, the flux of the neutrino beam is ∼100 times that of the other 2 SBN detectors, these relative fluxes are simulated as a function of neutrino energy and shown graphically in Figure 4 [6]. Consequently, the number of events expected during the full exposure of the experiment is around 7,000,000. A breakdown in terms of individual processes is given in Figure 5 [6]. Combining these huge statistics with the exceptional resolution capabilities of the liquid argon TPCs will allow SBND to make unprecedentedly high-precision cross-section and oscillation measurements. Working both in conjuction with MicroBooNE and ICARUS, and as a stand-alone experiment, SBND should produce some exciting and extremely important results.

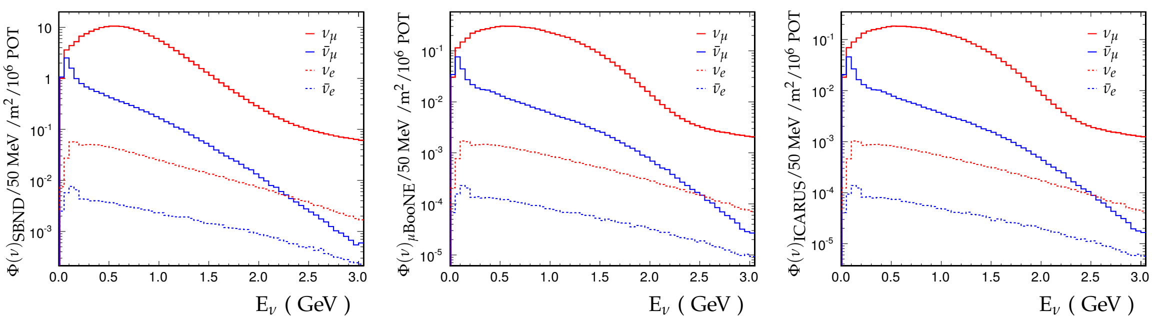

Figure 4: *From left to right, the BNB fluxes of SBND, MicroBooNE (μBooNE and ICARUS. From these plots it can be seen that SBND's flux will be ∼100 times the other two [6].*

Process		No. Events
	ν_μ *Events*	
CC 0 π	$\nu_\mu N \to \mu + Np$	**3,551,830**
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + nucleons + 1\pi^\pm$	**1,161,610**
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + nucleons + \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu + nucleons + \geq 1\pi^0$	497,963
NC 0 π	$\nu_\mu N \to nucleons$	1,371,070
NC 1 $\pi^\pm$	$\nu_\mu N \to nucleons + 1\pi^\pm$	260,924
NC $\geq 2\pi^\pm$	$\nu_\mu N \to nucleons + \geq 2\pi^\pm$	31,940
NC $\geq 1\pi^0$	$\nu_\mu N \to nucleons + \geq 1\pi^0$	358,443
Total ν_μ & ν_e events		**7,251,948**

Figure 5: *Some expected statistics for the entire exposure of SBND, broken down into some of the processes by which the neutrino may interact [6].*

SBND will be 5m long, 4m tall and 4m wide holding a total of 112 tonnes of liquid argon in its active volume. As an LArTPC, SBND will function in mostly the same way as described earlier and in Figure 3, although it will have some unique features. Figure 6 gives an idea of how the detector will be constructed.

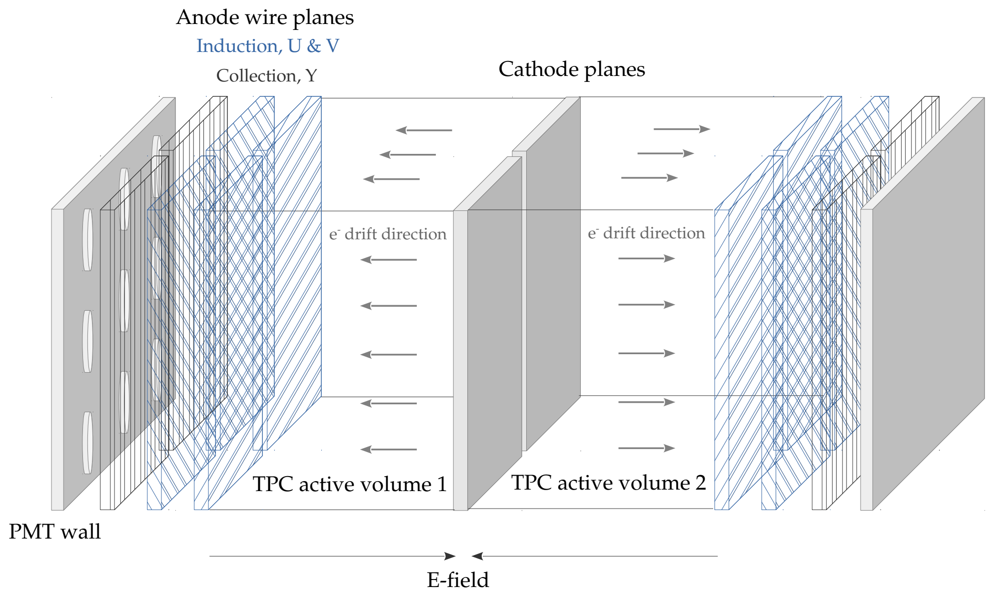

Figure 6: *A diagram to give an idea of how the SBND detector will look. It features many similarities to the standard liquid argon TPC design, but applies the concept of multiple modules - this is a possibility for the structure of DUNE [6].*

Unlike the typical TPC setup, SBND will have 2 cathode planes, 4 anode planes and 2 time projection chambers. The cathode planes will lie side-by-side, positioned at the join between the two TPCs. The anode planes will also lie in twos next to one another, with a pair residing on the opposite wall to the cathode plane of each TPC. This allows for 2 electric fields and therefore 2 opposing drift directions. In the same way as shown in Figure 3, there will be 3 wire planes to each anode plane. In the gaps between two adjacent anode planes, electrodes will divert the approaching particles towards the nearest active parts of the plane [6]. The multiple module system may well be a feature of the next generation TPC detectors such as DUNE.

3. Neutrino Interaction Phenomenology in the few-GeV Energy Range

3.1. Dominant topologies

3.2. Golden channel

3.3. Signal

3.4. Potential backgrounds

*3.5. **Maybe some results here?***

4. Theory and Recent Measurements of CC0π Cross-Section

4.1. Cross-sections

- Why?
  - Simulation
  - GENIE
- Historical
- Current knowledge
- Needs for future
  - LArTPCs
  - Statistics

Inc. equations

4.2. Method

4.3. Unfolding

4.4. Results

Plots and cross-section values

5. A Global Fit of CC0π Data

5.1. Experiments involved

5.2. Process

5.3. Results

6. Prospects for a CC0π Measurement at SBND and Sensitivity Esimates

6.1. SBND sensitivity

6.2. Future

7. Discussion

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