The CHIPS R&D Programme: Reconstruction

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Abstract. The CHIPS R&D programme aims to demonstrate significant cost reduction in the building of large neutrino detectors, whilst contributing to the global knowledge on the CP-violating phase in neutrino oscillations. A series of event reconstruction algorithms have been developed considering the charge and time information from all of the photomultiplier tubes to reconstruct charged particle tracks. A particle identification algorithm was developed using two artificial neural networks to select charged-current $\nu_e$ interactions from $\nu_\mu$ backgrounds. It has been demonstrated that using a 6% photocathode coverage of 3” photomultiplier tubes can provide the required performance from the particle identification to achieve the goals of the experiment.

1. Introduction
The CHIPS R&D programme aims to dramatically reduce the cost of large water Cherenkov neutrino detectors whilst helping to constrain the value of the CP-violating phase in neutrino oscillations, $\delta_{CP}$. The detector will be placed in a flooded mine pit in northern Minnesota. The pit water will provide both the structural support and the cosmic overburden, removing the need for major civil engineering. Furthermore, the detector will only be used to study beam neutrinos, meaning that the very low energy threshold requirements of other similar detectors are not necessary, enabling a much sparser photodetector array to be considered.

The event reconstruction software is required to distinguish charged-current (CC) $\nu_e$ signal interactions from the background CC $\nu_\mu$ and neutral-current (NC) $\nu$ events. The reconstruction method calculates the likelihood of measuring a given charge at a given time for each PMT for a given particle track hypothesis, and uses information from all PMTs whether they received an energy deposit or not. The method can be divided into two main parts, with one part predicting the charge and the other predicting the time. The charge component was written from scratch, but following the techniques developed by the MiniBooNE experiment [1, 2]. The time component was developed entirely from first principles.

2. Geometry Studies
A 10 kt detector called CHIPS-10 was simulated using a dedicated GEANT4 [3] simulation to be a 20-sided polygonal prism, 12.5 m in radius and 20 m in height. The photomultiplier tubes (PMTs) are placed on the barrel region walls and on the top and bottom caps. Three different options for the PMT layout were considered: 10” PMTs at 10% photocathode coverage and 3” PMTs at both 10% and 6% photocathode coverage.

Charged-current quasi-elastic (CCQE) $\nu_e$ and $\nu_\mu$ interactions were generated using GENIE [4] according to the predicted energy distribution for CHIPS-10 exposed by the NuMI beam [5]. The CCQE $\nu_e$ events were then reconstructed using a single electron track hypothesis. The
Table 1. The resolutions of various reconstructed parameters from single ring electron (muon) track fits to a sample of CCQE $\nu_e$ ($\nu_\mu$) interactions with energies following those expected from the NuMI beam.

| Sample     | Geometry   | Position (cm) | Reconstruction | Resolution | Time (ns) | Direction (°) | Energy (MeV) |
|------------|------------|---------------|---------------|------------|-----------|---------------|--------------|
| CCQE $\nu_e$ | 10 inch, 10% | 35            | Position      | 0.9        | 2.1       | 208           |
|            | 3 inch, 10%  | 35            | Time          | 0.84       | 1.9       | 210           |
|            | 3 inch, 6%   | 38            | Direction     | 0.89       | 2.1       | 211           |
|            | 10 inch, 10% | 47            | Energy        | 1.35       | 2.6       | 113           |
| CCQE $\nu_\mu$ | 3 inch, 10% | 44            |               | 1.14       | 2.7       | 110           |
|            | 3 inch, 6%   | 51            |               | 1.28       | 3.0       | 113           |

CCQE $\nu_\mu$ sample was likewise reconstructed using a single muon track. Table 1 summarises the calculated resolutions for the vertex position, vertex time, particle direction and particle energy for both sets of interactions. The results show that the 3" PMTs perform at least as well as the 10" PMTs, and that the 6% coverage of 3" PMTs shows only a minor degradation in performance compared to the 10% coverage case.

3. Particle Identification

The particle identification capabilities of CHIPS-10 were tested for the 3" PMT geometry option with 6% photocathode coverage. Samples of $\nu_e$ and $\nu_\mu$ CC and NC interactions were produced with energies according to the NuMI beam. In what represents the simplest case, the goal was to reconstruct these interactions using a single ring fit where each event was reconstructed twice: once with a muon track and once with an electron track. The particle identification must use the information from these two fits to determine the true interaction type.

Two artificial neural networks (ANNs) were developed and trained using the TMVA [6] package in ROOT [7]. The first of these networks was designed to separate CC $\nu_e$ interactions from CC $\nu_\mu$ events, and was trained on samples of CCQE interactions in order to concentrate on the leptonic ring features. The second network was designed to separate NC $\nu$ interactions from CC $\nu_e$ events, and was trained on CCQE $\nu_e$ events plus a sample of NC interactions that survived a cut of 0.8 on the output of the first network. This ensured that the interactions were not "muon-like", hence ensuring that the second ANN did not try to perform the same separation as the first.

The full $\nu_e$ and $\nu_\mu$ samples were used to optimise the cut values on the two output variables from the ANNs, $a_{e\mu}$ and $a_{NC}$. The optimal cut values were found to be 0.9 and 0.75, respectively using the product of the CC $\nu_e$ selection efficiency and purity as the figure of merit. Figure 1 shows the output variable distributions for the two ANNs, with each shown after the application of the other ANN output classifier to show more clearly the purpose of the two ANNs.

4. Conclusion

Figure 2 shows the selection efficiency after the application of the cuts on the two ANN classifier variables for the CC $\nu_e$ (and separately, the CCQE component), CC $\nu_\mu$ and NC components, and also the purity of the CC $\nu_e$ selection. The efficiencies shown compare well with those values assumed in the CHIPS LOI [8]. Averaging over the energy spectrum, the CC $\nu_e$ selection has an efficiency of 30% and a purity of 58%. The selection will be further improved by a $\pi^0$ fitter which will reduce the background from the electron-like NC interactions containing a $\pi^0$. 
Figure 1. The output distribution from each of the ANNs, shown after the application of the preselection and the optimised cut on the other ANN output, for CC $\nu_e$, CCQE $\nu_e$, CC $\nu_\mu$ and NC interactions. The cut on the other ANN was applied in order to show more clearly the events that each network was designed to separate. The black line and arrow shows the optimised cut value on the displayed network output variable used to select $\nu_e$ events. The components are not stacked.

Figure 2. The selection efficiency for CC $\nu_e$, CCQE $\nu_e$, CC $\nu_\mu$ and NC interactions, and the purity for the CC $\nu_e$ component.

References

[1] Patterson R B 2007 A search for muon neutrino to electron neutrino oscillations at $\delta (m^2) > 0.1$ eV$^2$ Ph.D. thesis Princeton U.
[2] Patterson R B, Laird E M, Liu Y, Meyers P D, Stancu I and Tanaka H A 2009 Nucl. Instrum. Meth. A608 206–224 (Preprint 0902.2222)
[3] Allison J et al. 2006 IEEE Trans. Nucl. Sci. 53 270
[4] Andreopoulos C et al. 2010 Nucl. Instrum. Meth. A614 87–104 (Preprint 0906.2517)
[5] Adamson P et al. 2016 Nucl. Instrum. Meth. A806 279–306 (Preprint 1507.06690)
[6] Hocker A et al. 2007 PoS ACAT 040 (Preprint physics/0703039)
[7] Brun R and Rademakers F 1997 Nucl. Instrum. Meth. A389 81–86
[8] Adamson P et al. 2013 Proceedings, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013 (Preprint 1307.5918)