Declaration

This thesis represents the original work of the author except for where specific references are made to the work of others. The presented work has not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. Due to the collaborative nature of particle experiments, the thesis relies upon the work of collaborators from the Short-Baseline Near Detector (SBND) and other experiments.

The overviews of Heavy Neutral Leptons (HNLs) and physics of liquid argon time projection chambers, given in Chapters 2 and 3 respectively, contain work to which the author did not contribute. References assign credit for the work and figures presented.

The overview of SBND given in Chapter 4 relies on work performed by the entire SBND collaboration [1, 2]. Figures not made by the author are labelled with references to the source. In the scope of detector installation, the author helped with the cabling of the Photon Detection System (PDS) boxes and their installation to the detector alongside B. Carlson and B. Bogart. The author also installed the PDS readout electronics, under the guidance of M. Stancari and W. Badgett.

Also in Chapter 4, the flux prediction employs the Booster Neutrino Beam simulation developed in MiniBooNE [3]. The flux simulation was performed by Z. Pavlovic and the flux reader was developed by M. Del Tutto. The author assisted with validating the fluxes at SBND after updating to the kaon reweighting scheme from SciBooNE [4] .

In the simulation framework of SBND described in Chapter 5, the author contributed to the development of the MeVPrtl generator for simulating beyond standard model particles. This generator was a joint effort of SBND and ICARUS collaborators, led by G. Putnam. The author developed and validated the physics of HNL simulation with R. Alvarez-Garrote and L. Pelegrina-Gutierrez. The implementation of the generator into SBND was performed together with R. Alvarez-Garrote. Moreover, the author identified and helped implement a fix in the GENIE generator to enable the timing simulation of neutrino interactions, which necessitated the HNL analysis using Monte Carlo (MC) samples.

In Chapter 6, the charge reconstruction toolkits, Wirecell [5] and Pandora [6], were developed before the author's involvement. The author updated the track-shower separation algorithm within Pandora, with the help of E. Tyley and D. Brailsford. The PDS and CRT reconstruction and analysis tools were contributed by SBND collaborators with credits provided in the references. Most importantly, the author would like to thank F. Nicolas-Arnaldos, R. Alvarez-Garrote, D. Garcia-Gamez and J. I. Crespo-Anadon, who pioneered the timing reconstruction using the SBND PDS, which the HNL analysis relies on.

The study of the DAQ timing performance in Chapter 7, relies on work performed by SBND collaborators. The hardware and software of the White Rabbit timing system as well as the CRT Sharps was setup before the author's involvement. The author contributed in the calibration and installation of the SPEC-TDC module and the cabling of timing signals under the guidance of M. Stancari, G. A. Lukhanin and W. Badgett. The timing characterisation of FEB modules was performed with the help of M. Stancari and H. Lay. The timing characterisation of CAEN digitisers received inputs from M. Stancari.

In Chapter 8, the presented work in the scope of charge calibration was performed under the guidance of M. Mooney and many discussions with G. Putnam and J. Mueller. A summary of results from the ICARUS collaboration is included, with references assigned credit in the work and figures presented.

The selection of HNLs in Chapter 9 contains many elements shared across SBND collaborators. MC samples used in the selection were a collaborative work with H. Lay and R. Alvarez-Garrote. The selection software was built with help from H. Lay. Moreover, the cosmic rejection tool CRUMBS was developed by H. Lay, the flash matching tool OpT0 was developed by L. Tung and the particle identification tool Razzled was developed by H. Lay with groundwork done by E. Tyley. Finally, the selection sparked many useful discussions with R. Alvarez-Garrote, L. Pelegrina-Gutierrez and J. I. Crespo-Anadon.

The uncertainty reweighting in Chapter 10 was performed using the framework shared across the SBND and ICARUS collaboration, developed before the author's involvement. The author would like to thank H. Lay, J. Mueller, and J. Kim for their help in understanding uncertainty treatments. The procedure to set upper limits was performed using the `pyhf` package [7], with references assign credit for the employed statistical methods [8–10]. Finally, the author would like to thank A. M. Szelc, whose idea was to search for HNLs by exploiting their lateness, that started this entire thesis.

Vu Chi Lan Nguyen
July 2024

References

[1] P. A. Machado et al., "The Short-Baseline Neutrino Program at Fermilab", Annual Review of Nuclear and Particle Science **69**, 363–387 (2019).

[2] R. Acciarri et al. (SBND), "Construction of precision wire readout planes for the Short-Baseline Near Detector (SBND)", JINST **15**, P06033 (2020).

[3] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), "Neutrino flux prediction at miniboone", Phys. Rev. D **79**, 072002 (2009).

[4] G. Cheng et al. (SciBooNE Collaboration), "Measurement of K^+ production cross section by 8 GeV protons using high-energy neutrino interactions in the SciBooNE detector", Phys. Rev. D **84**, 012009 (2011).

[5] C. Adams et al., "Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative evaluation with MicroBooNE simulation", Journal of Instrumentation **13**, P07006 (2018).

[6] J. S. Marshall et al., "The Pandora Software Development Kit for Pattern Recognition", Eur. Phys. J. C **75**, 439 (2015).

[7] L. Heinrich et al., *pyhf: v0.7.6*, version 0.7.6, https://github.com/scikit-hep/pyhf/releases/tag/v0.7.6.

[8] G. Cowan et al., "Asymptotic formulae for likelihood-based tests of new physics", Eur. Phys. J. C **71**, [Erratum: Eur.Phys.J.C 73, 2501 (2013)], 1554 (2011).

[9] T. Junk, "Confidence level computation for combining searches with small statistics", Nucl. Instrum. Meth. A **434**, 435–443 (1999).

[10] A. L. Read, "Presentation of search results: The CL_s technique", J. Phys. G **28**, edited by M. R. Whalley et al., 2693–2704 (2002).