

1 Introduction

Deep beneath the Amundsen-Scott station on the geographic South Pole, lurks a telescope in the ice. This observatory hunts for some of the most elusive particles in our universe, hoping they may answer foundational questions about nature, and glean insight into new physics that the Genevan collider—or its potential successors—may never be able to.

The IceCube Neutrino Observatory was built between 2005 and 2010, but its heritage stretches back several decades. Spanning one cubic kilometer of Antarctic ice, the telescope consists of some 60 strings, hot water drilled into the ice, with each string containing a number of photomultiplier tubes, capable of detecting photons originating from processes involving neutrinos—the aforementioned elusive particles.

Measurements of certain neutrino properties may help us understand phenomena such as why the universe is matter-dominated¹ and dark matter². IceCube is also capable of searching for point-like sources³, and serves in the SuperNova Early Warning System⁴. But one thing is the ability to observe derived photons in Antarctic ice; another is reconstruction of this light in order to infer properties of the originating particles. To date, classical methods, such as PegLeg⁵ and Retro Reco* have mostly been used for this purpose, but the burgeoning proliferation of the use of machine learning (ML) for scientific discovery⁶ inspires the development of new methods for this cause.

Whereas classical methods require a hypothesis and thus preset logic, ML “changes these [problems] from logic problems to statistical problems”[†]. That is to say, given a large enough—or rather, a representative enough—dataset, an ML algorithm may find statistical similarities in disparate neutrino events sharing similar underlying properties, giving the network an ability to predict these same properties for previously unseen data. As a “machine learning model is almost like a pure function at inference time”[‡], owing to the universal approximation theorems, it should be possible to construct an ML reconstruction algorithm that is both faster, preciser, more extensible, captures a wider spectrum and is more future-proof than the current methods.

*<https://github.com/IceCubeOpenSource/retro>

[†]<https://www.ben-evans.com/benedictevans/2019/9/6/face-recognition>

[‡]Brennan Saeta, <https://www.swiftbysundell.com/podcast/58/>

The intention of this thesis is to explore that proposition, specifically for up-going muon neutrinos in the sub-teraelectronvolt range.

This problem is selected as it is the focus of the oscillations group at IceCube, studying neutrino oscillations. The current best reconstruction algorithm for this case, Retro Reco, can take minutes to reconstruct a neutrino, while an ML-based approach can be expected to reconstruct several thousand each second. An additional focus will be the IceCube upgrade⁷, which will install additional improved detectors, and for which there is no current functioning reconstruction algorithm.

For that, we need an understanding of the particle physics and machine learning techniques involved, which is explored in chapters 2 and 3, respectively.

The data used for any ML problem is even more important than the algorithm used and technically the dataset should be designed with ML applications in mind to be of optimal use. This is not the case, as IceCube's data structure is not well suited for a machine learning task, and thus chapter 4 goes into both the design of the databases used for the datasets and the selection and features of the data itself.

Chapter 5 goes into the design of the algorithm, including such details as loss functions and optimizers, while chapter 6 shows results and comparisons to existing methods.

Lastly, a summary and outlook is given in chapter 7.

With the introduction out of the way, let us start by looking at the particle physics involved in the interactions relevant for IceCube.

2 Particle physics

The fact that neutrinos oscillate is one of the more exciting findings in particle physics. Because it points to something we cannot explain, namely that neutrinos have non-zero mass, researching this phenomenon might open the window into new physics beyond the Standard Model, much as the ultraviolet catastrophe led to quantum mechanics and the lack of evidence for a luminiferous aether led to relativity.

In the following we shall start by introducing said model, briefly touch on the weak interaction, and explain the phenomenon of neutrino oscillations and what problems it may help solve.

2.1 The Standard Model

The Standard Model is a

3 Machine learning

4 Data

5 Design

6 Results

7 Summary and outlook

Bibliography

- [1] Hiroshi Nunokawa, Stephen Parke, and Jose W. F. Valle, “CP violation and neutrino oscillations,” *Progress in Particle and Nuclear Physics* **60**, 338–402 (2008) (cited on page 1).
- [2] Sebastian Baur, “Dark matter searches with the IceCube upgrade,” arXiv:1908.08236 [astro-ph, physics:hep-ph] (2019) (cited on page 1).
- [3] IceCube Collaboration et al., “Time-integrated neutrino source searches with 10 years of IceCube data,” *Physical Review Letters* **124**, 051103 (2020) (cited on page 1).
- [4] Lutz Köpke, “Supernova neutrino detection with IceCube,” *Journal of Physics: Conference Series* **309**, 012029 (2011) (cited on page 1).
- [5] Martin Leuermann, “Testing the neutrino mass ordering with IceCube DeepCore,” PhD thesis (Rheinisch-Westfälische Technische Hochschule, 2018), 159 pages (cited on page 1).
- [6] Maithra Raghu and Eric Schmidt, “A survey of deep learning for scientific discovery,” arXiv:2003.11755 [cs, stat] (2020) (cited on page 1).
- [7] Aya Ishihara, “The IceCube upgrade – design and science goals,” arXiv:1908.09441 [astro-ph, physics:physics] (2019) (cited on page 2).