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-dominated[1] and dark matter[2]. IceCube is also capable of searching for point-like sources[3], and serves in the SuperNova Early Warning System[4].

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 PegLeg[5] and Retro Reco[*] have mostly been used for this purpose, but the burgeoning proliferation of the use of machine learning (ML) for scientific discovery[6] 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

[*] https://github.com/IceCubeOpenSource/retro

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

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.

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 upgrade[7], which will install additional improved detectors, and for which there is no current functioning reconstruction algorithm.

1.1 Flow

To weave a common thread through this document, and ensure the reader is informed about the big picture throughout, the following section presents the flow of the thesis.

The story of an interaction in IceCube from physics to analysis proceeds at a very high level as follows: The universe is created with mechanisms that only allow a certain chirality of neutrinos to interact with forces other than gravity (section 2.2 on page 6). At some point an interaction will create such a particle (section 2.3 on page 6), which oscillates between different flavors (section 2.4 on page 6). As chance allows some neutrinos to interact in or around the instrumented ice, new particles are created that in turn send out a specific form of light (section 2.5 on page 6) which the photomultiplier tubes (section 3.2 on page 13) can detect. Today each in-ice digital optical module contains one photomultiplier tube. With the IceCube upgrade this changes (section 3.8 on page 13), and new optical modules will be fitted with additional photomultiplier tubes which should help with determining the direction of neutrinos. The detector is set up with certain triggers in differing levels (section 3.3 on page 13), to ensure that not just any light is recorded and saved to disk. Even further processing is done, as the bandwidth from pole to America is quite low, and so care must be taken

[‡]Brennan Saeta, Software Engineer - TensorFlow, https://www.swiftbysundell.com/podcast/58/

in the choice of what to actually send down the wires for analysis. When the data arrives for analysis, different level of cleaning takes place to root out noise (section 3.5 on page 13). This pipeline also attempts to classify event types, using decision trees, until finally algorithms — none of them machine learning based — reconstruct neutrino properties of interest such as energy and direction (section 3.6 on page 13), and the events at all levels of cleaning are saved in an IceCube proprietary format, called I3 (section 3.7 on page 13).

With this part done, we turn towards machine learning generalities. First the basics of machine learning in general (section 4.1 on page 14), then deep learning in particular (section 4.2 on page 14). Special attention is given to temporal convolutional neural networks (section 4.3 on page 14), as this is the architecture used. Because loss functions are such an important part of any deep learning project, a section is devoted to this concept as well (section 4.4 on page 14), and for the most part, before data can be meaningfully trained in a neural network, some form of data transformation is required (section 4.5 on page 14).

The last part of the thesis concerns the work by the author. The data format provided by IceCube is not machine learning friendly, so a new solution fixing those shortcomings was built (section 5.3 on page 15). So that the reader is on the same page as the author, plots and metrics used for comparison are explained. The opponent algorithm is detailed (section 6.2 on page 16), before the structure of the data itself used in training is explained (section 6.3 on page 16) and the algorithm laid out (section 6.4 on page 16).

2 Particle physics

Neutrinos are some of the universe's most interesting and mysterious particles, and offer one of the better paths to researching some still unsolved problems in physics. The Large Hadron Collider nailed down the final missing piece of the model, the Higgs boson, but questions still remain; and some of them concern neutrinos.

The masses of the neutrinos themselves is a mystery, but sterile neutrinos may also be a dark matter candidate and the possible CP-violating phase in the PMNS matrix may help explain baryon asymmetry. Needless to say, the more we discover about this little particle, the better we know the universe.

The concept of neutrino oscillations has the ability to constrain the previously mentioned CP-violating phase of the neutrino mixing matrix[8] and so the better we are able to measure this, the better the constraint will be.

This chapter will seek to outline the physics behind the interactions that are captured in the IceCube detector, including the concept of Cherenkov radiation, which is of critical importance to the process.

First, we shortly need to touch on what The Standard Model of particle physics is.

2.1 The Standard Model

The Standard Model (SM) of particle physics is the foundation of modern particle physics research. It was patched together during the 20th century by an extreme amount of scientific collaboration and country-level spending.

The theory itself is a gauge quantum field theory, the mathematics of which is not particularly relevant to this thesis. However, the theory describes some fundamental interactions, of which the so-called weak one is of importance to the neutrino.

It is possible, and indeed probably quite pedagogical, to discuss the SM through the Dirac equation:

$$\left(\mathrm{i}\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0, \tag{2.1}$$

with $\mu \in \{0, 1, 2, 3\}$ and where γ represents the gamma matrices $\{\gamma^0, \gamma^1, \gamma^2, \gamma^3\}$ and ∂ is the partial differential operator. This equation governs the fields corresponding to spin-½ particles, of which neutrinos are an example, and the gamma matrices are defined by their anti-commutation relation

$$\{\gamma^{\mu}, \gamma^{\nu}\} = \gamma^{\mu}\gamma^{\nu} + \gamma^{\nu}\gamma^{\mu} = 2\eta^{\mu\nu} I_4, \tag{2.2}$$

where η is the Minkowski metric with signature $(+---)$ and I_4 is the 4 dimensional identity matrix.

Equation (2.1) came about out of needing to reconcile special relativity and quantum mechanics. In short, the wave equation needed to be Lorentz invariant. The Dirac equation leads to the form of the matrix elements in the different possible interactions, for example the electromagnetic scattering of an electron and tau (seen in fig. 2.2 on page 8),

$$\mathcal{M} = -e^2 \left[\bar{u}_e(p_3)\gamma^{\mu}u_e(p_1)\right] \frac{g_{\mu\nu}}{q^2} \left[\bar{u}_{\tau}(p_4)\gamma^{\nu}u_{\tau}(p_2)\right], \tag{2.3}$$

where $u_{\ell}, \ell \in \{e, \tau\}$ represents the spinor of a particle, $\bar{u}_{\ell}, \ell \in \{e, \tau\}$ the anti-spinor and the momenta $\{q, p_1, p_2, p_3, p_4\}$ correspond to fig. 2.2 on page 8. In this case, an electron and a tau lepton scatter by exchanging a photon, with momentum q, which changes the momentum of both the electron and the tau. The standard model describes these fundamental interactions of the universe, embodied in Feynman diagrams such as fig. 2.2 on page 8, also useful for neutrino physics. Equation (2.3) shows the prominence of the gamma matrices in the fundamental interactions, which is of some importance in the weak interaction, to be discussed in section 2.2 on the following page.

Figure 2.1 on page 7 shows the standard representation of The Standard Model. Charged fermions may participate in the electromagnetic interactions via the photon, while all fermions participate in the weak interaction, and only quarks feel the strong interaction.

2.2 The weak interaction

2.3 Neutrino interactions

2.4 Neutrino oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

2.5 Cherenkov radiation

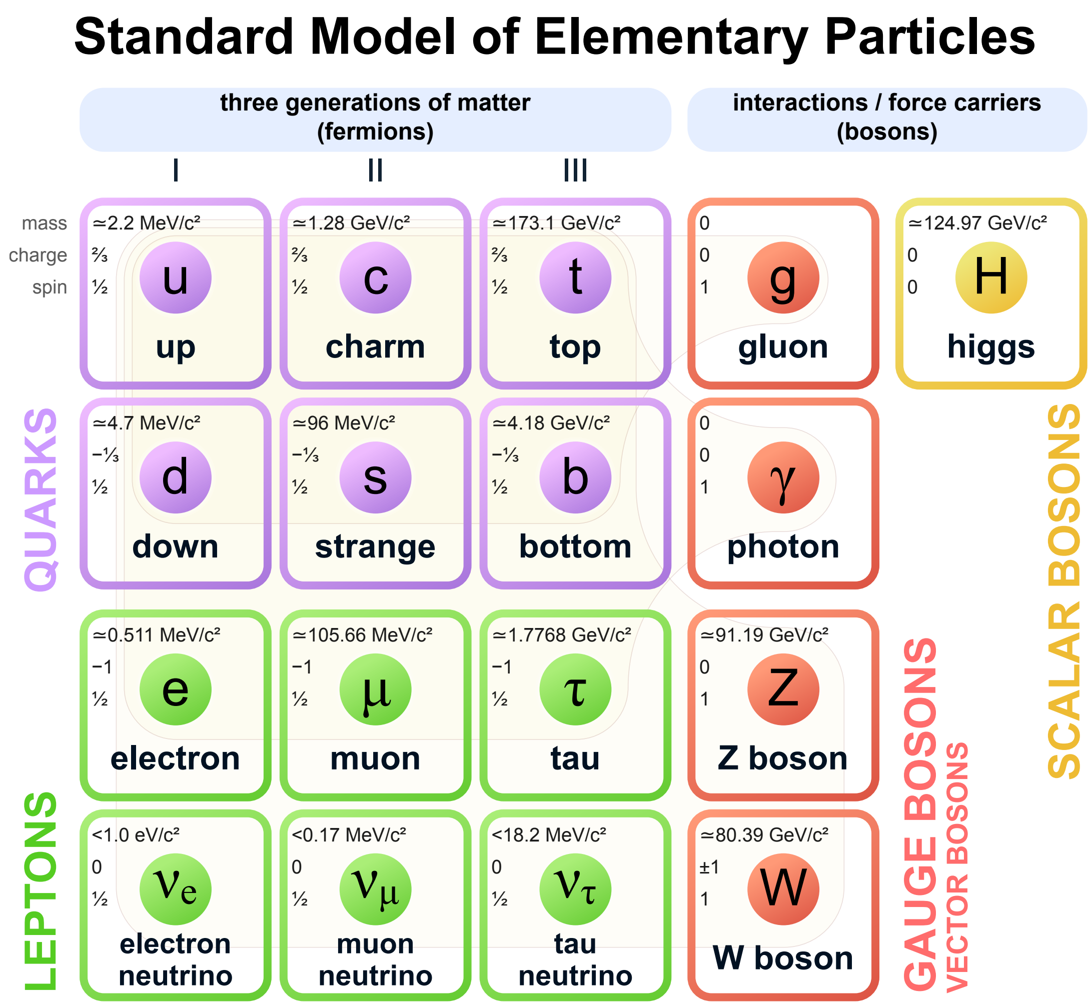

Figure 2.1: The fermions and bosons of The Standard Model of particle physics. Image from[9]

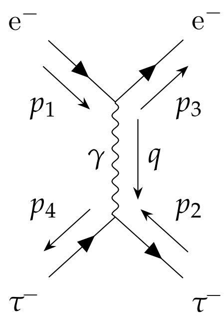

Figure 2.2: Feynman diagram showing the *t*-channel scattering of an electron and a tau.

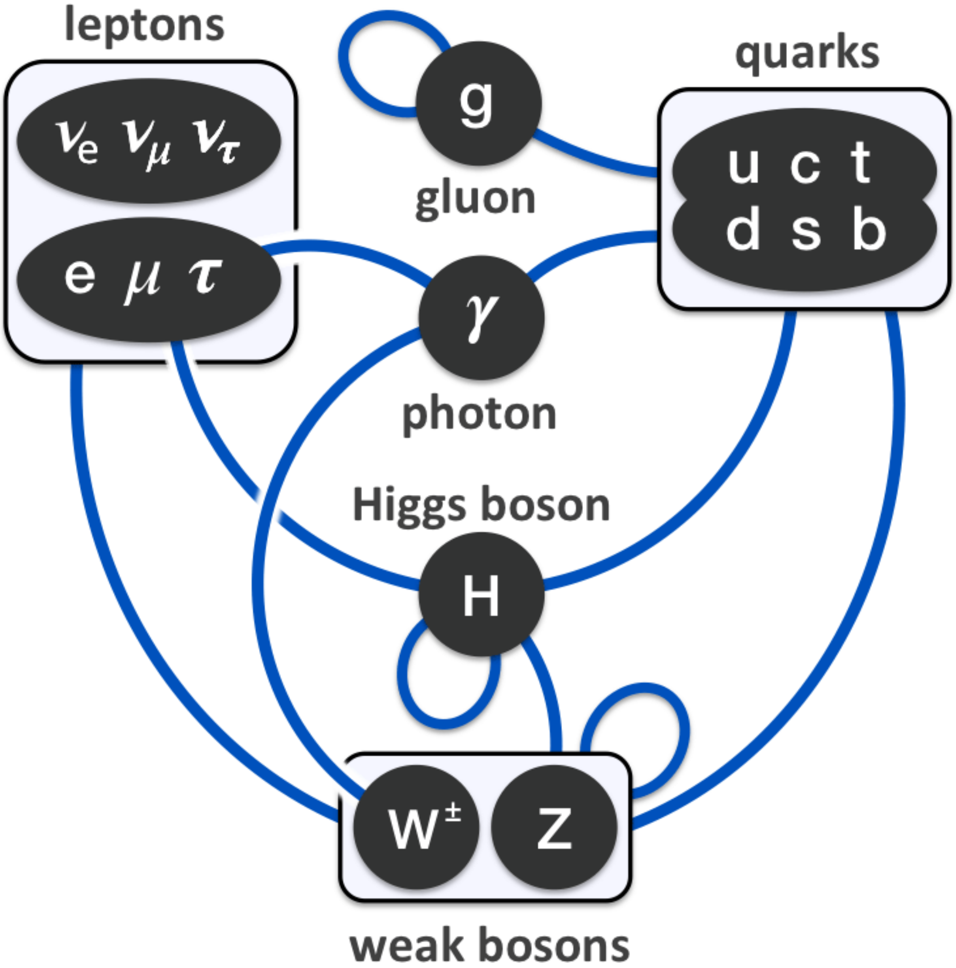

Figure 2.3: The possible interactions in the SM between fermions and bosons. Image from[10]

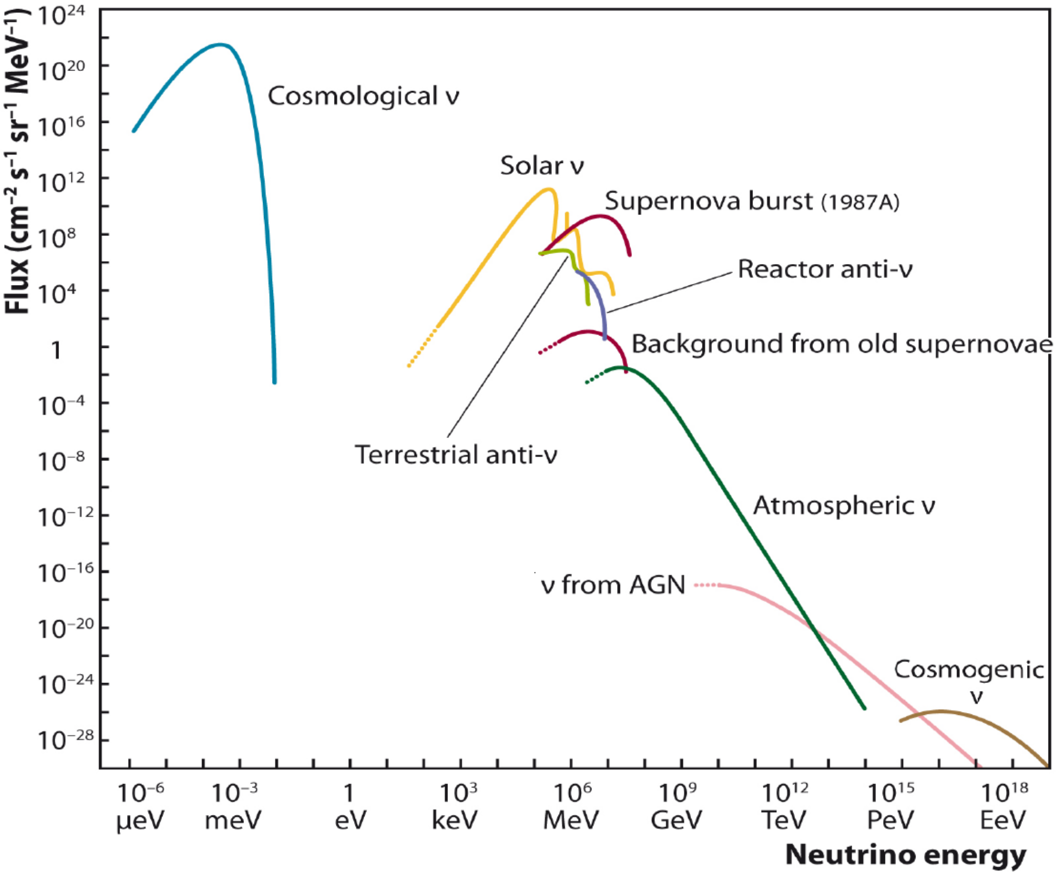

Figure 2.4: Neutrino spectrum. Image from[11].

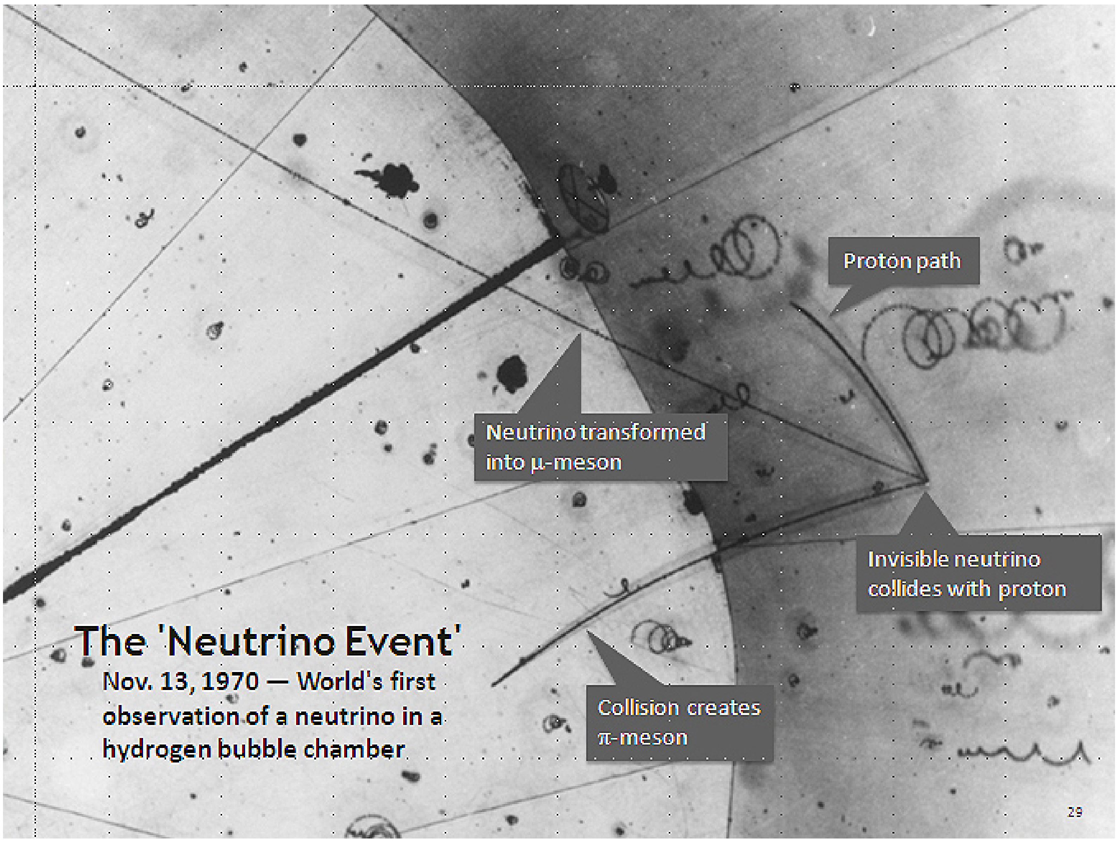

Figure 2.5: First neutrino seen in a bubble chamber. Image from[12].

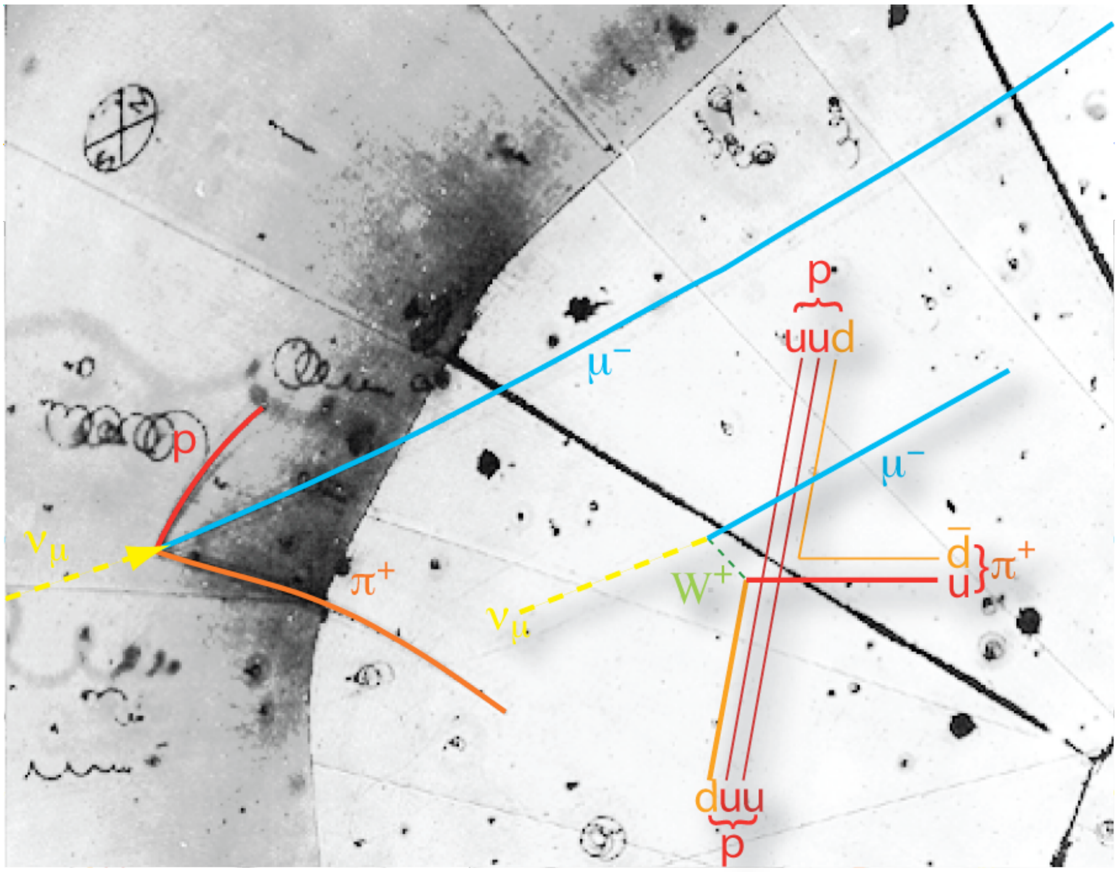

Figure 2.6: Bubble chamber neutrino event with annotation. Image from[13].

3 IceCube

3.1 Detector

3.2 DOMs

3.3 Triggers

3.4 Post processing

3.5 Levels

3.6 Current reconstruction methods

3.7 I3 file format

3.8 IceCube upgrade

4 Machine learning

4.1 ML basics

4.2 Deep learning

4.3 Temporal convolutional neural networks

4.4 Loss functions

4.5 Data transformation

5 Data

5.1 Monte Carlo simulation

5.2 OscNext

5.3 SQLite

6 Design

6.1 Plots and metrics

6.2 Opponents

6.3 Data structure

6.4 Algorithm

7 Results

8 Summary and outlook

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