# First partial draft of my Thesis

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## Abstract

This is a dissertation outline using the style guidelines defined by the University of Glasgow.

Dedication. (Is what you need.)

## Acknowledgements

ACK

## Declaration

The research results presented in this thesis are the product of my own work. Appropriate references are provided when results of third parties are mentioned. The research presented here was not submitted for another degree in any other department or university.

**Sven-Patrik Hallsjö**

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# Chapter 1

# Introduction to Neutrino Physics

This chapter is aimed at giving an introduction to the physics used in the thesis.

## 1.1 Research Goals

This research aims to construct a prototype Magnetized Iron Neutrino Detector (Baby MIND) at the European Organization for Nuclear Research (CERN) and understand the performance of the detector to reconstruct charged particle tracks at a test beam at CERN and neutrino interactions with our collaborators in the WAGASCI collaboration at a neutrino beam at the JPARC facility in Japan. This is discussed further in chapter 3.

## 1.2 Theory

While measuring radioactive beta decay in the first two decades of the 20th century, physicists discovered what was then an anomaly. At the time it was thought that beta decay occurred as a two body process in which a neutron ($n$) decays to a proton ($p$) and electron ($e^-$). If this were the case, the energy of the proton and electron should be discrete and add up to the energy of neutron. However experiments showed that the electron could have a continuous spectrum of energy values, violating the energy conservation law, as seen in figure 1.1. In order to solve this anomaly, a third particle, the neutrino ($\nu$), was postulated by Wolfgang Pauli [1] and then incorporated into the beta decay by Enrico Fermi [2]. The neutrino was postulated as a neutral particle with mass of less than $1\%$ of the proton mass and a spin of 1/2. For consistency, the particle used in the beta decay was changed to be noted as the antineutrino with the electron flavour, or just electron antineutrino $\bar{\nu}_e$. The addition of another particle changed the decay to $n \rightarrow p + e^- + \bar{\nu}_e$ and introduced the weak interaction model, as seen in figure 1.2.

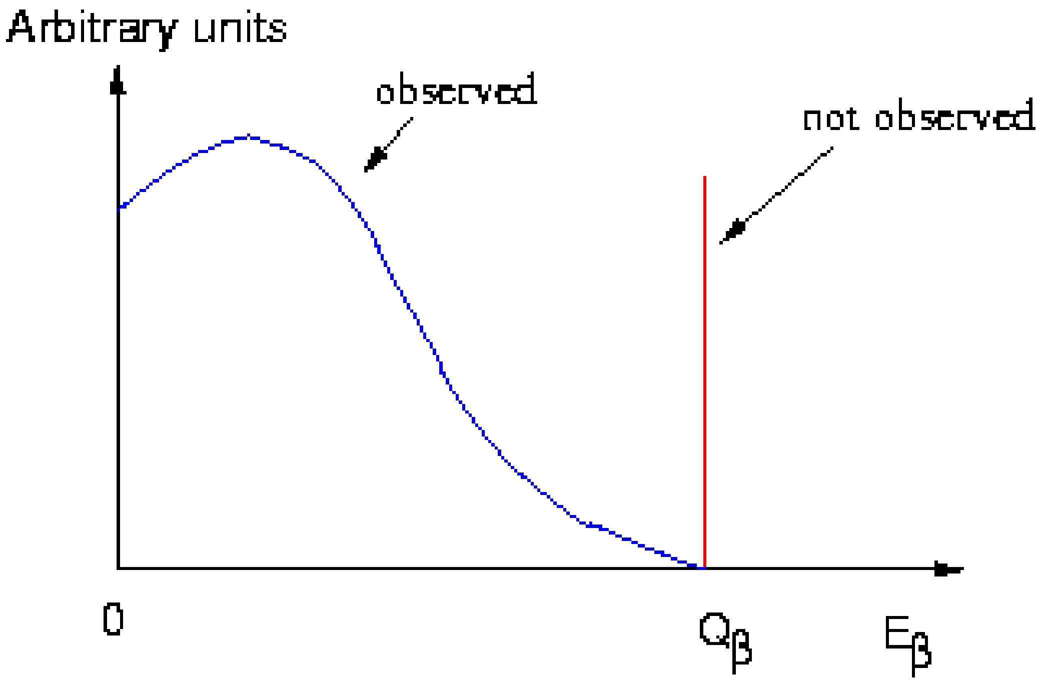
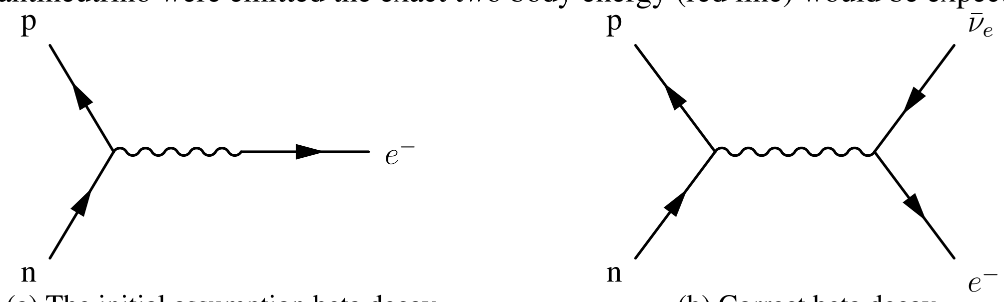



Figure 1.1: The kinetic energy spectrum of the emitted electron from beta decay (blue line). If no antineutrino were emitted the exact two body energy (red line) would be expected. [3]




(a) The initial assumption beta decay

(b) Correct beta decay

Figure 1.2: Feynman diagrams showing beta decay.

It would take another twenty years until the neutrino was experimentally discovered by the Savannah river reactor experiment in 1956 [4] and awarded the Nobel prize in 1995.

After the discovery of the electron neutrino ($\nu_e$), several neutrino experiments were performed and led to the discovery of two other neutrino types/flavours, the muon neutrino ($\nu_\mu$) and the tau neutrino ($\nu_\tau$) [5, 6, 7].

### 1.2.1 Standard Model neutrino

The standard model of particle physics or simply the Standard Model (SM) categorizes all the fundamental particles that have been discovered experimentally and the mathematics of their properties and how they interact [8, 9]. Currently there are two fundamental types of particles which are modelled as point like, quarks (fractional charge) and leptons (integer charge), seen in figure figure 1.3. Aside from these gauge bosons, the force mediators, are in the standard model. The split can also be seen as ferminos (fractional spin) and bosons (integer spin). **All gauge bosons are bosons (as the name implies) and all quarks and leptons are fermions.**

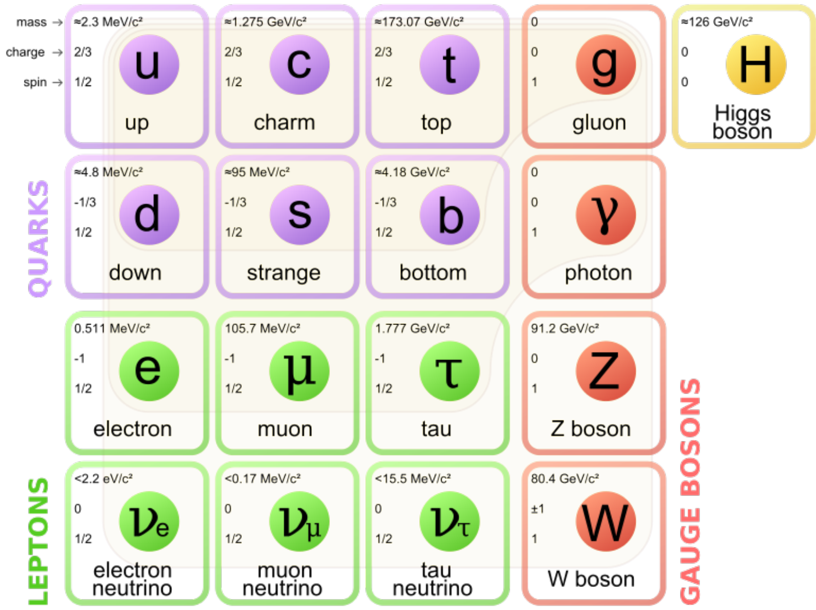



Figure 1.3: The standard model of particle physics where the three first columns represent the so called generations, starting with the first. [10]

The experiment by Goldhaber, Grodzins, and Sunyar concluded that neutrinos only exist in a left handed chiral state, meaning that momentum and spin are oppositely aligned. They also concluded that anti-neutrinos only exists in the right handed state [11]. In the initial or unexpanded SM, [12], only fermions which have both chiral states have mass through the Brout-Englert-Higgs mechanism [13]. At the time this lead to the definition of the neutrino as a massless particle, however in subsection 1.2.4 it will be shown that neutrino oscillations require at least one of the neutrinos to have mass. This indicates that the unexpanded SM needs to be extended to account for this new physics.

### 1.2.2 Neutrino interactions

As discussed previously, neutrino interactions are described by the weak interaction model. This model is split into two different parts depending on which boson mediates the interaction. Charge Current (CC) interactions changes the final state quarks or leptons by one unit of electric charge and are mediated by the $W^+$ and $W^-$ bosons while Neutral Current (NC) interactions do not change the charge and are mediated by a $Z^0$ boson. To look at possible interactions of neutrinos described in the Standard Model of particle physics, one needs to look at the quantum field theory description of the interactions[14, 15]. Sample Feynman diagrams showing these interactions can be seen in figure 1.4 and figure 1.5.

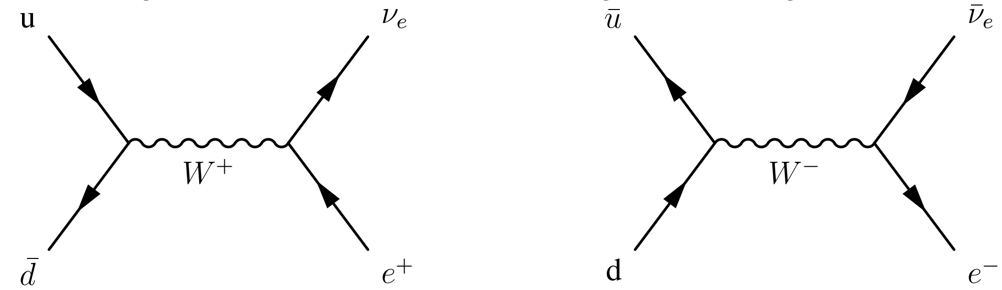



Figure 1.4: Feynman diagrams showing an example of a charge current interaction.

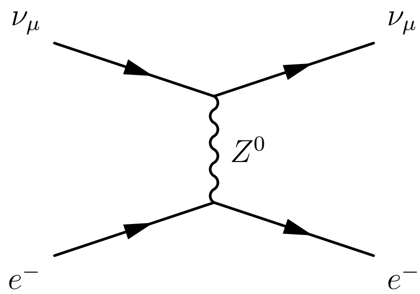



Figure 1.5: Feynman diagram showing an example of a neutral current interaction.

From the Feynman diagrams one can calculate the probability of the interaction occurring, details can be found in [14]. Two interesting examples of this is to compare the probability for comparing similar interactions in Quantum ElectroDynamics (QED), or simply electromagnetic interactions, and weak interactions, comparing CC and NC. In figure 1.6 a comparison is made between QED and a weak interaction. Calculating the cross-sections when $E << M_Z$ the following quotient is produced: $\frac{\sigma_{Weak}}{\sigma_{QED}} \approx (\frac{s}{M_Z^2})^2$ where s is the square of the center of mass energy, $M_Z$ is the mass of the Z-boson. Currently the Z-boson mass is $91.1876 GeV$ [16] but since s varies it is hard to give a value to the quotient. For the energy range where $E << M_Z$ this quotient varies from $0.01 \rightarrow 0.1225$. With the current values QED is approximately 100 times more likely to occur than a weak interaction..

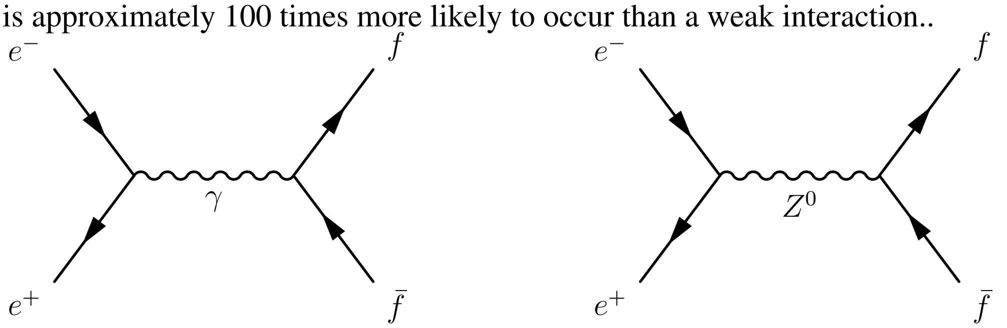



Figure 1.6: The QED and the weak contributions to the scattering electron-positron to any quark or lepton pair.[1]

Looking at the following CC and NC examples figure 1.7 with electrons and muon neutrinos, so that the final states can be distinguished. The cross sections of both can be written

[1]If $f = e^-$ a T-channel diagram has to be added as well

as $\sigma_{CC}(\nu_\mu e^-) \approx \frac{G_F^2 s}{\pi}$ and $\sigma_{NC}(\nu_\mu e^-) \approx \frac{G_F^2 s}{\pi}\left[(-\frac{1}{2}+\sin^2\theta_W)^2+\frac{1}{3}\sin^4\theta_W\right]$ where $G_F$ is the Fermi coupling constant and $\theta_W$ is the Weinberg angle. This gives a relation CC and NC as $\frac{\sigma_{CC}}{\sigma_{NC}} = 1/\left[(-\frac{1}{2}+\sin^2\theta_W)^2+\frac{1}{3}\sin^4\theta_W\right] \approx 11$. With the current values CC is approximately 11 times more likely to occur than NC.

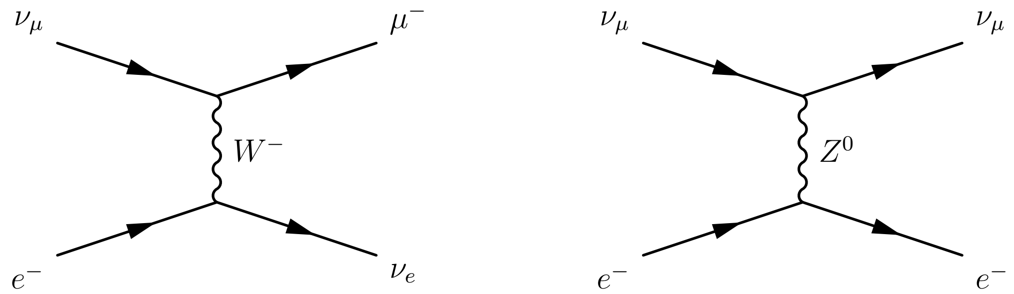



Figure 1.7: Feynman diagrams, CC(Left) and NC(Right) with the same initial states.

## 1.2.3 Missing neutrinos

The Homestake experiment measured the flux of electron neutrinos and found only around 1/3 of the expected value from the theoretical model of the nuclear reactions in the core of the sun [17]. One of the possible explanations for the deficit was neutrino oscillations proposed by Bruno Pontecorvo [18]. This theory was later verified at both the Sudbury Neutrino Observatory (SNO) [19] and Super-Kamiokande [20]. All three experiments were awarded Nobel prizes and have paved the way for physics beyond the Standard Model.

## 1.2.4 Neutrino mass and oscillation in vacuum

While looking at an analog of neutral kaon mixing for neutrinos Bruno Pontecorvo, in 1957, developed the concept of neutrino-antineutrino transitions [18]. Even though to date no matter-antimatter oscillation had been observed, the concept formed the foundation of lepton mixing, which was developed by Maki, Nakagawa, and Sakata [21] and refined into a neutrino flavour oscillation model by Bruno Pontecorvo. They managed to show that neutrino mixing is a natural outcome of adding neutrino mass to a gauge theory [18]

The relation between the flavour and mass eigenstates can be expressed as,

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle\,,\, |\bar{\nu_\alpha}\rangle = \sum_i U_{\alpha i}\,|\bar{\nu_i}\rangle \tag{1.1}$$

where $|\nu_\alpha\rangle$ is a neutrino with a fixed flavour, $\alpha$ is one of $\{$e,$\mu$,$\tau\}$ and $|\nu_i\rangle$ is a neutrino with a fixed mass. $U$ is the Pontecorvo-Maki-Nagawa-Sakata (PMNS) matrix in (1.2),

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix} \tag{1.2}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ with $\theta_{ij}$ the three mixing angles and $\delta_{CP}$, $\phi_2$ and $\phi_3$ are complex phases. The parameters $\phi_2$ and $\phi_3$ are only non-zero if neutrinos are their own antiparticles, which is still unknown at the time of writing this [16].

The interpretation is similar to that of a time-dependent quantum state, the probability of finding a neutrino in a specific state is related to the mass states through the PMNS matrix in which the elements are time dependent. It can also be thought of as a rotation in space. The derivations of the oscillation probability for assuming only two neutrinos and also for three neutrinos are often given in literature for instance it is given in [12]. The three neutrino flavour state 1.1 in an initial beam evolves in time as:

$$|\nu_\alpha(t)\rangle = \sum_i e^{-iE_it}U_{\alpha i}\,|\nu_i\rangle \tag{1.3}$$

Which gives the Probability of flavour evolution as

$$P_{\nu_\alpha\to\nu_\beta}(t) = |\langle\nu_\beta\,|\nu_\alpha\rangle|^2 \quad = \sum_{i,j}\left|U_{\alpha i}U^*_{\beta i}U\alpha j^*U_{\beta j}\right|\cos[(E_i - E_j)t - arg(U_{\alpha i}U^*_{\beta i}U\alpha j^*U_{\beta j})] \tag{1.4}$$

$$E_\alpha = \sqrt{\vec{p}^2 + m_i^2} \approx |\vec{p}| + \frac{m_i^2}{2\,|\vec{p}|} \tag{1.5}$$

Which can then be rewritten to depend on distance travelled by the beam (x) if using a relativistic approximation of the energy-momentum relationship 1.5 as

$$P_{\nu_\alpha\to\nu_\beta}(x) = |\langle\nu_\beta\,|\nu_\alpha\rangle|^2 \quad = \sum_{i,j}\left|U_{\alpha i}U^*_{\beta i}U\alpha j^*U_{\beta j}\right|\cos[\frac{2\pi x}{L_{ij}} - arg(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})] \tag{1.6}$$

where the oscillation length $L_{ij} = \frac{4\pi|\vec{p}|}{\left|m_i^2 - m_j^2\right|}$ and $\vec{p}$ is the 3-momentum of our initial beam.

It can be seen that if $m_i^2 - m_j^2 = 0$ this probability becomes $0$ which contradicts the experimental results. This means that atleast one of the neutrinos must have non-zero mass which currently is not explained through the Standard Model. Also that if $U_{\alpha i}$ is real, which is related to $\delta_{CP} = 0$, then $arg(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}) = 0$.

Current experimental focus lies with trying to measure values for all of these parameters and one of the most interesting for understanding more about the Big Bang theory is the complex phase $\delta_{CP}$. This is known as the CP-violating phase which, if non-zero, would state that there is a difference between how normal and anti-neutrinos oscillate. **Experimental value so far of CP**

Table 1.1 provides the current mass limits for neutrinos, note that currently there is no lower limit since it is only known that at least two of the neutrinos must have mass.

| Particle | 95% CL Mass limit (MeV) | 95% CL Anti-particle mass limit (MeV) |
|---|---|---|
| $\nu_e$ | $< 0.225$ | $< 2 \cdot 10^{-3}$ |
| $\nu_\mu$ | $< 0.19$ | No Data |
| $\nu_\tau$ | $< 18.2$ | No Data |

Table 1.1: Current upper neutrino mass limits [16]

### 1.2.5 CP-violation, baryogenesis and leptogenesis

According to the current understanding of the Big Bang theory, matter and anti-matter were created in equal amounts[22]. This gives rise to one of the major unsolved problems in physics, where is all the anti-matter? If the answer was simply that antimatter exists somewhere else in the universe, then we should see the annihilation horizon, where matter and anti-matter interact, however there are no signs of this. There has also not been any sign of this in the cosmic background radiation[22].

Through observations of the universe, much more matter has been found compared to anti-matter. One direct measurement was AMS-01, which measured the ratio of anti-helium to helium in the universe to be of the order of $10^{-6}$ [23]. Another measurement, AMS-02 seems to confirm the first measurement and build on the results [24]. From these experimental results, a mechanism is needed to explain why the antibaryon component of the universe is $\sim 10^{-9}$ to that of baryons. As of now our current models can not account for the difference thus there must be unknown processes that account for this.

The unknown process has been split into two different fields, baryogenesis, looking at direct CP-violation in the baryon-antibaryon asymmetry and leptogenesis, CP-violation in the leptons that translates to a baryon asymmetry. Leptogenesis will be covered in this thesis as it relates to neutrinos also it should be added that there are theories which explain baryogenesis through leptogenesis.

If neutrinos violate CP (Charge, Parity) by their oscillations being different for neutrinos and anti-neutrinos, this could explain the matter anti-matter imbalance that has been observed. CP-violation exists in the Standard Model but it can not explain the observed difference [14], and measurements of the CP-violation in neutrino oscillations have not yet been able to show any conclusive results [25].

### 1.2.6 Current theory of leptogenesis

Basing on similar reasoning to the discussion above, andrei Sakharov proposed three necessary conditions that any interaction which would produce matter antimatter imbalance must satisfy [26]. These conditions are:

- Baryon number violation.
- C-and CP-violation.
- Deviation from thermal equilibrium.

The first conditions is very important in that it related cosmological models with models in particle physics. It also gives us a way to produce an excess of baryons over anti-baryons, as long as there is no reverse interaction, hence requiring the C violation. CP-violation is needed to counteract the balancing as well and finally out of thermal equilibrium to get around CPT-symmetry. As briefly mentioned previously the second condition is fulfilled in the SM, but not enough, and the third can always be satisfied. **However there is no way of violating baryon number conservation in the SM.**

In [27] a number of viable scenarios for baryogenesis are briefly discussed for instance Grand Unified theories, heavy Majorana neutrinos and supersymmetry.

### 1.2.7 How to detect neutrinos and neutrino oscillation

There is currently no way of seeing neutrinos directly, in comparison to for instance photons. **For that matter, what is direct?** Thus all experiments are based on looking at indirect detection by detecting interaction products. For instance beta decay figure 1.2 or the inverse (the charge conjugate) beta decay. Similar processes exist for all flavours of neutrinos, and the general limit is that neutrinos only interact weakly. All of the interacting particles, sans the neutrino, deposit energy when passing through matter. This energy can be measured by constructing a detector out of scintillating material which converts this deposited energy to photons. Finally these photons can be detected through conventional photo-detectors.

By looking at the oscillation probability (1.6) one can devise two main classes of experiments for neutrino oscillations.

Finding a distance x to the source where $P_{\nu_\alpha \to \nu_\alpha}(x) < 1$ it is possible to look at so called disappearance of the beam. At the detector, by comparing the expected neutrino flux to the observed one can provide evidence for neutrino oscillations. For the disappearing flavour there must be a probability, $P_{\nu_\alpha \to \nu_\beta}(x) > 0, \alpha = \beta$ for another flavour to appear. The second kind of experiment, denoted as appearance, is based on looking for interaction products which are impossible without oscillations. An example of this would be to see a positron from a muon neutrino beam. More on this can be found well described in [12] and examples of different detectors will be discussed in chapter 2.

## 1.3 Current Theories to explain neutrino mass

As discussed in subsection 1.2.1, it is clear that without having both types of chiral, neutrinos can not have mass through Brout-Englert-Higgs mechanism [13]. Currently there are two different approaches to explain the neutrino masses through processes which already exist in the SM by implying that some observations still have to be made.

**NEEDS TO BE EXTENDED.**

# Chapter 2

# Neutrino experiments

This chapter is aimed at putting the Baby MIND experiment into context of what has been done before, what experiments are under way and what experiments are planned.

## 2.1 Neutrino detector experiments

This section details some of the neutrino experiments that have and are taking place. The different experiments can be split into three different categories based on the primary neutrino source. The detector types are:

- Accelerator
- Atmospheric/Cosmic
- Reactor

Each will be described briefly before examples are given.

### 2.1.1 Accelerator

Currently accelerator facilities can produce muon, electron both normal and anti neutrinos. This is done by starting with a hydrogen plasma, protons, which is then accelerated at a target to produce a shower of pions and muons. By using a magnetic horn these can be split by charge and then aimed at another target to provide muon neutrinos.

The other way is using the electrons which have been split from the hydrogen plasma and a similar method used to produce electron neutrinos.

The advantage of these neutrinos are that the energy range is well known and can be quite well tailored, the flux is huge compared to other methods. However the energy distribution will be quite wide because of the decay processes involved. It is also hard to produce a clean beam without background.

#### 2.1.1.1 K2K / T2-K

After the success of Super-Kamiokande, the K2K-experiment[28] was created with the main difference of using a well understood muon neutrino beam pointing at the Super-Kamiokande detector at a distance of 250 km. It was the first neutrino oscillation measurement where both the source and detector were controlled, it observed the disappearance of muon neutrinos and found results that were consistent with Super-Kamiokande.

The next improvement came with the T2K-experiment[29], which was also a long-baseline neutrino oscillation experiment with a more powerful beam from the JPARC facility to Super-Kamiokande, at a distance of 295 km. The experiment wanted to improve the understanding of the neutrino oscillation parameters. T2K was able to successfully observe the appearance of muon to electron neutrino oscillations and find evidence that the third mixing angle $\theta_{13}$ is not zero. This is still an ongoing experiment.

#### 2.1.1.2 MINOS

MINOS [30] is also a muon neutrino disappearance experiment, consisting of one near and one far detector and using the NuMI [31] beam at Fermilab, to better understand the neutrino beam and showed results consistent with Super-Kamiokande and the K2K experiments. This is one of the first MIND (Magnetised Iron Neutrino Detector) types build along with CDHSW [32].

#### 2.1.1.3 NOvA

After MINOS the next step using the NuMI [31] beam is the NOvA [33] experiment, which is also an electron neutrino appearance experiment and hopes to be able to determine the mass hierarchy of neutrinos.

#### 2.1.1.4 MINERvA

The MINERvA (Main INjector ExpeRiment $\nu$-A)experiment [34] will also use the NuMI [31] beam to study neutrino-nucleus scattering to improve models of neutrino-nucleus scattering to reduce systematic uncertainties in results from oscillation experiments.

#### 2.1.1.5 MiniBooNE

MiniBooNE[35] continued on what was started by MINOS but had the principle aim on improving neutrino mass measurements.

### 2.1.2 Atmospheric/Cosmic

For these experiments either solar, or other cosmological sources are used to provide the neutrinos. The main advantages are that the energy can be very high and it is possible to use the earth to remove all background providing an extremely clean signal. However, it is impossible to control the source and difficult to get many events due to the low fluxes expected from astrophysical objects.

#### 2.1.2.1 SNO

The Sudbury Neutrino Observatory (SNO) [19] was build to make a definite measurement of solar neutrinos following on the measurements taken by the Homestake experiment [17]. It consists of an 1000 ton heavy water detector 2 km underground.

The experiment is currently replacing the heavy water with liquid scintilator and renaming it self as SNO+ [36].

#### 2.1.2.2 Super-K

Super-Kamiokande[37], an upgraded version of the Kamiokande water Cherenkov detector performed the first experimental observation that the neutrino has non-zero mass[20] and also managed to detect strong evidence of muon neutrino oscillation to tau neutrinos from the analysis of atmospheric neutrinos interacting in the water Cherenkov target.

#### 2.1.2.3 IceCube

The IceCube observatory [38] uses the enormous detection volume of the South Pole to detect Cherenkov photons produced in the ice from neutrino interactions.

### 2.1.3 Reactor

For these experiments all neutrinos are provided through nuclear fission which means that the energy spectra of the neutrinos are well known and there is very little background. On the other hand the energy range is limited to be quite low compared to accelerator neutrinos.

#### 2.1.3.1 Double Chooz

The Double Chooz experiment [39] uses antineutrino to improve the neutrino mixing angle $\theta_{13}$ as well as showed that these detectors can be used to ensure non-proliferation.

#### 2.1.3.2 Daya Bay

The Daya Bay experiment [40] main goal is to improve the measurement of $\theta_{13}$. It is improving results from Double Chooz. This is done by combining electron antineutrinos from eight identical detectors placed at three locations around the detector.

#### 2.1.3.3 KamLAND

KamLAND, the Kamioka Liquide scintilator Anti-Neutrino Detector, was build in 2002 and helped investigate if there were any neutrino oscillations by looking at anti electron neutrinos emitted from distant reactors [41].

## 2.2 MIND detector

Magnetized Iron Neutrino Detectors (MINDs) have been operated in several experiments such as MINOS [30]. This type of detector, with magnetized steel plates and scintillation plates, is well suited to provide large mass for neutrino experiments and is able to provide momentum measurements by using range and curvature calculations as well as providing charge identification. A MIND type detector has been selected as the baseline detector for a neutrino factory [42, 43], since it is the cheapest and most effective way of producing a large magnetized volume. This has provided the motivation for creating a prototype detector to perform a number of studies.

Since water Cherenkov and liquid argon detectors have been established or actively studied for future very large scale neutrino oscillation experiments, a MIND type detector is not foreseen to be used as the main interaction medium for any planned upcoming experiments.. A MIND type detector can however be used to provide charge identification of muons if positioned downstream of any neutrino target which is not magnetized.

## 2.3 Future neutrino experiments

### 2.3.1 Hyper-K

The Hyper-Kamiokande Experiment[44] builds on the T2K-experiment[29] by improving the neutrino beam at JPARC, and building a 500 kton water Cherenkov detector, which aims to improve the sensitivity for $\delta_{cp}$.

### 2.3.2 DUNE

LBNF/DUNE[45] is a new experiment aiming at looking at the full range of $\delta_{cp}$ with greater sensitivity than before by improving on the MINOS [30] experiment, and performing an electron neutrino appearance measurement with a high-powered neutrino beam from Fermilab and a 40 kton liquid argon detector at a distance of 1300 km, in the Homestake mine in South Dakota.

### 2.3.3 nuStorm experiment/Neutrino factory

One concept to achieve a high number of neutrino events from a well-understood neutrino beam is the so called Neutrino Factory [46], which will create a high number of electron and muon neutrino events from the decay of high-energy muons.

A nuSTORM facility, which could be seen as the first stage towards a neutrino factory, is expected to have sensitivity for sterile neutrinos with a MIND type detector [47] upto $10\sigma$ compared to previous measurements.

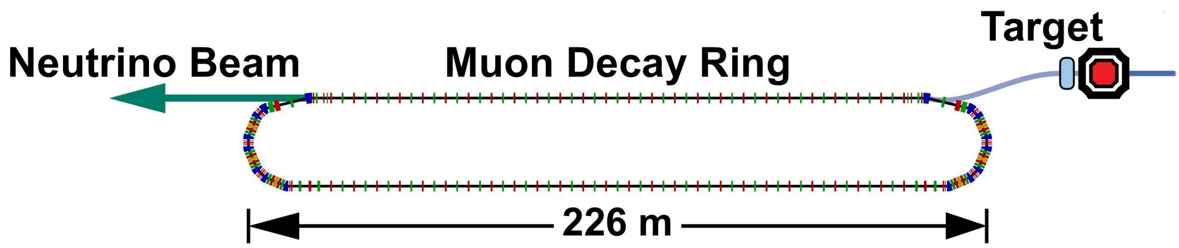



Figure 2.1: A schematic of a nuSTORM facility [48].

The neutrino factory has the capacity to improve the precision of neutrino oscillation measurements, since the neutrino beam from the decay of muons can be determined with high accuracy. The beam produces one bunch of $\mu^+$ and one bunch of $\mu^-$, so the facility can make measurements of $\nu_\mu$ and $\bar{\nu}_e$ and $\bar{\nu}_\mu$ and $\nu_e$ simultaneously. Using this $\delta_{cp}$ can be decisively explored, with an expected accuracy of $\Delta\delta_{CP} \sim 5°$ [46].

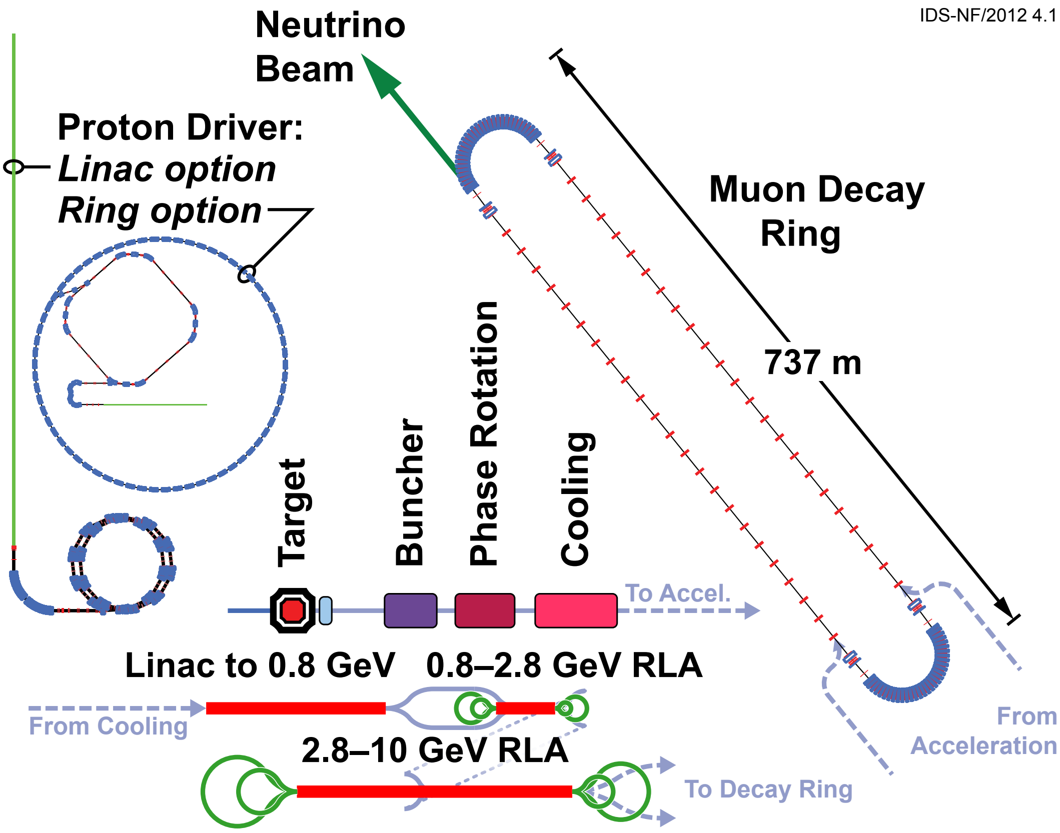



Figure 2.2: Schematic diagram of the Neutrino Factory [48].

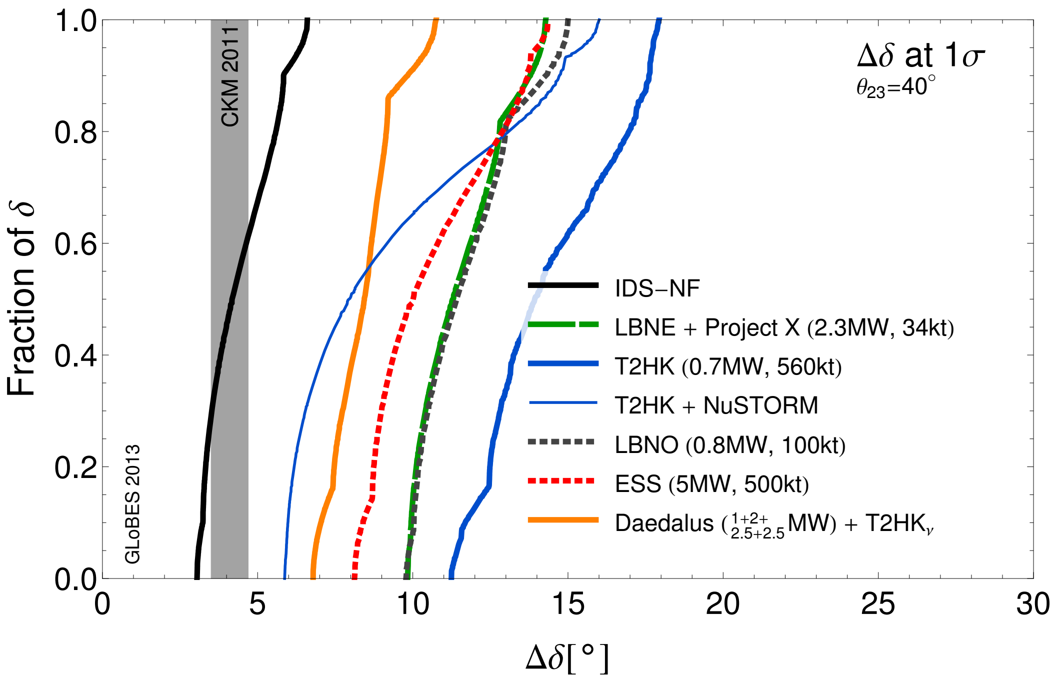



Figure 2.3: Expected precision for a measurement of the $\delta_{cp}$ at a Neutrino Factory compared to alternate neutrino oscillation facilities [48].

# Chapter 3

# Baby MIND + WAGASCI

## 3.1 Baby MIND

The prototype Magnetized Iron Neutrino Detector (Baby MIND) [49] has the principal aim to study muon charge identification efficiencies in order to get estimates for a future Neutrino Factory. A secondary aim is to compare simulations from GEANT4 [50] to data taken from the detector to be able to verify the properties of muon interactions at momentum ranges of 0.5 to 10 GeV/c.

The prototype is currently being built at CERN, where it will be provided with a charged particle test beam to fully understand the characteristics of the detector. Once the detector has been characterised, the plan is to integrate it into the WAGASCI experiment in Japan to improve measurements of the ratio of neutrino interaction cross-sections on water and carbon and also to place it downstream to provide improved charge identification. The main way of improving these measurements is by reducing systematic errors that arrive from the nuclear effects in water [49].

### 3.1.1 Timeline

The current timeline for the construction of Baby MIND can be seen in figure 3.1. These are the following milestones expected to be met by the Baby MIND project:

- Beam tests characterization at CERN in May 2017.
- Shipment to Japan in July 2017.
- Installation in Japan,WAGASCI pit, in September for operation in October 2017.

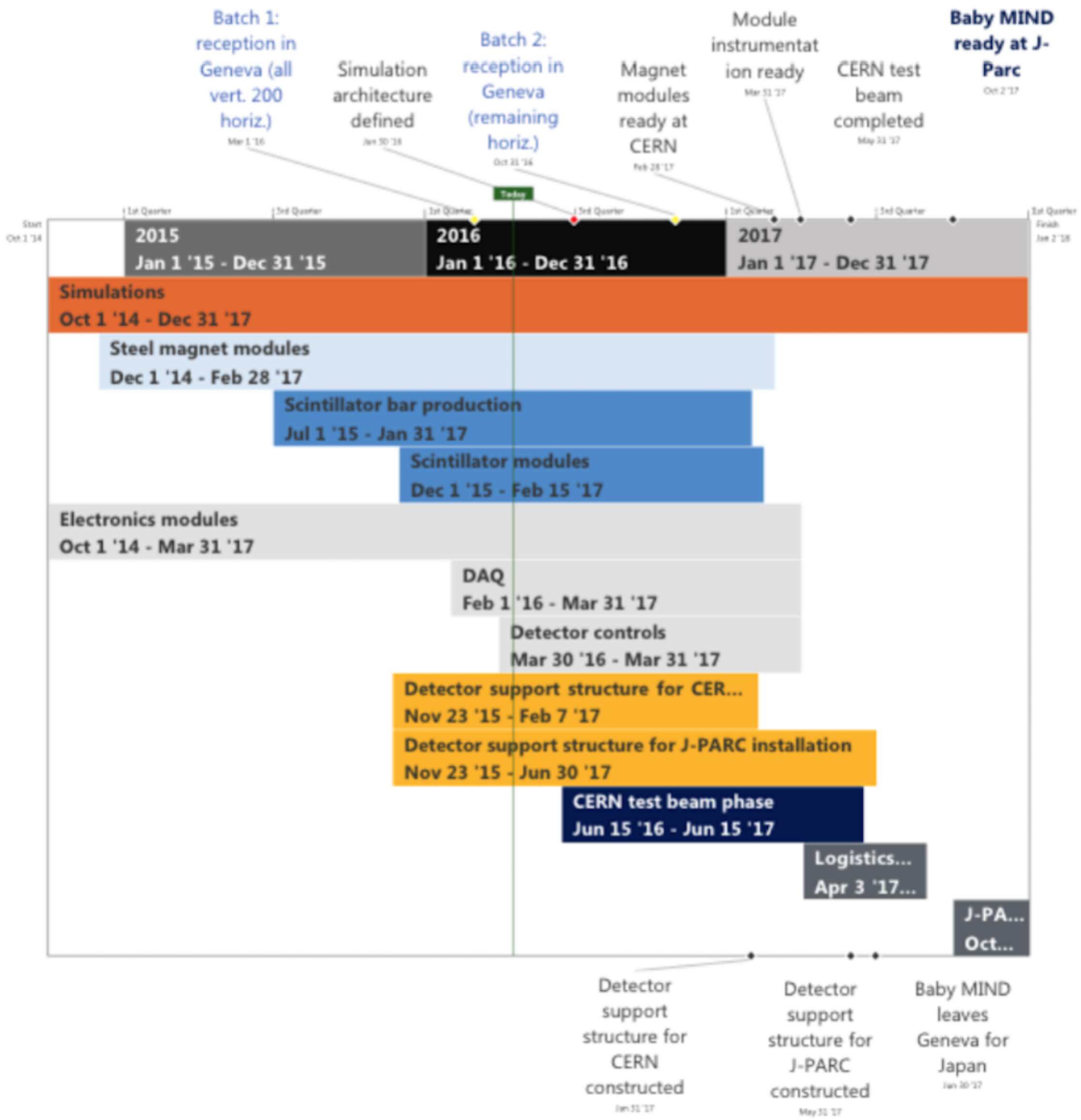



Figure 3.1: The current Baby MIND timeline

### 3.1.2 Collaboration

The Baby MIND collaboration is comprised of 44 scientists from nine different institutions, and is part of the CERN Neutrino Platform as experiment NP05 [51]. The 3000 Multi-Pixel Photon Counters (MPPC, also known as Silicon Photomultipliers, SiPM) were provided by the University of Glasgow. Glasgow is also responsible for the simulation software.

### 3.1.3 Layout

As discussed in subsection 2.2, a MIND type detector requires a magnetized volume as well as interaction medium to deflect the particle tracks and scintillating elements to detect the particle hits. A schematic overview of the detector can be seen in figure 3.3. The magnetised


Figure 3.2: The current Baby MIND collaboration

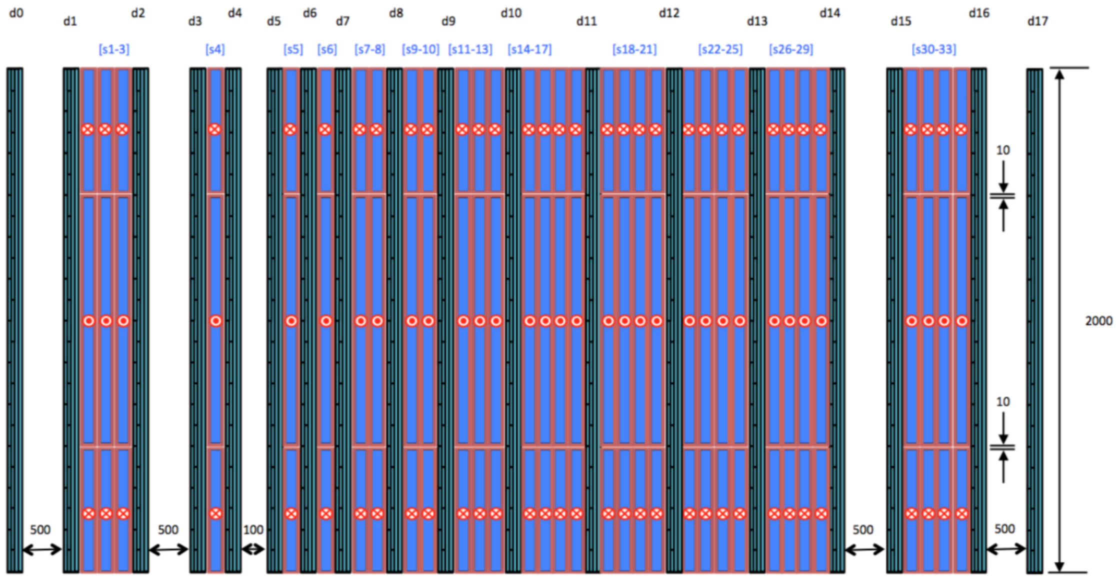



Figure 3.3: The current Baby MIND design

volume for the Baby MIND has been chosen as a total of 33 steel plates both to have a simple magnetic field as well as being modular and cheaper than the alternatives. An overview of the magnetic field is seen in figure 3.4 with two open slots in order to cover the entire plate with coils with currents in opposite directions. This improves the flux return, contains the stray fields and reduces power dissipation outside of the plates compared to a single conducting coil wound on the surface of each individual plate.

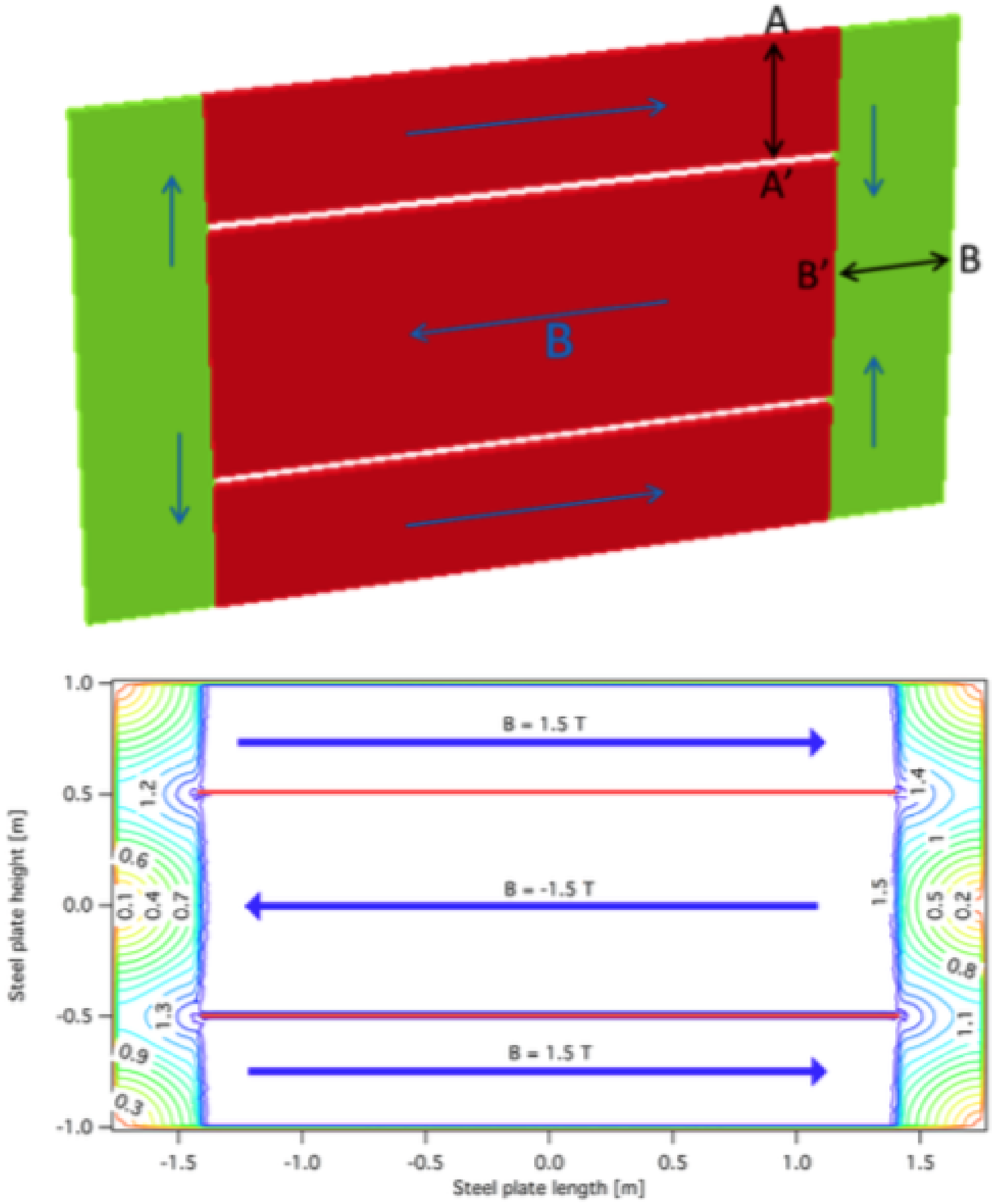



Figure 3.4: The current Baby MIND magnetic field map

The scintillating elements, seen in figure 3.5, have been chosen as 18 scintillating modules consisting of four planes per module, two oriented along the horizontal direction with and two oriented in the vertical direction, each to produce good horizontal and vertical resolution of the particle interactions

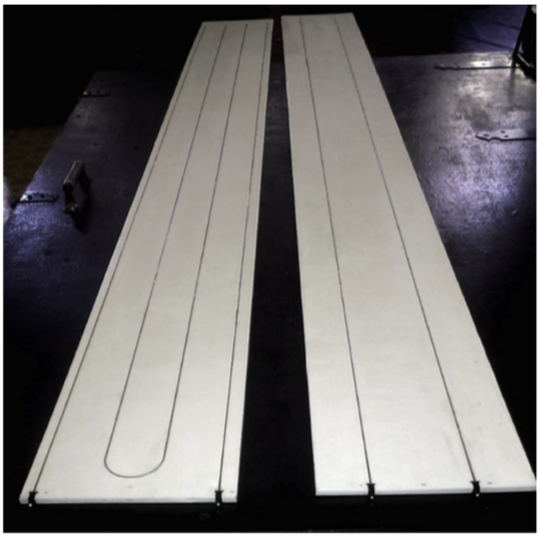


Figure 3.5: One of the vertical scintillator bars.

# 3.2 WAGASCI/T59

## 3.2.1 Collaboration

The current WAGASCI collaboration is given in figure 3.6.

## 3.2.2 Layout

A new water-scintillator detector, WAGASCI (WAter- Grid-SCIintilator-Detector) seen in figure 3.7, is proposed to reduce the systematic error in the T2K neutrino experiment.

## 3.2.3 Motivation

The main goals of the proposed detector are to improve the charge current cross section ratio between water and scintillator targets and to perform high-precision measurement of different charged current neutrino interaction channels.


Figure 3.6: The current WAGASCI collaboration

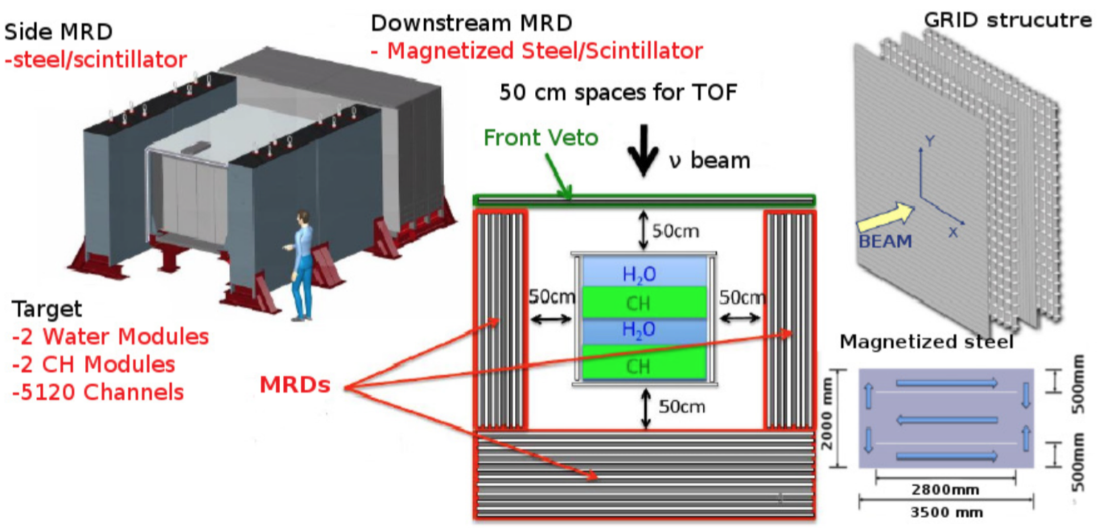



Figure 3.7: The basic structure of the WAGASCI detector including one of the possible designs for the MIND plates. [52].

# Appendix A

# Current results Year2

From last year the software has been completed and can handle neutrino and muon beam events in a generic MIND type detector. The main problem used to be how to handle multiple hit occupancy but this changed to be an issue with momentum reconstruction. The problem arose from bugs and incorrect use of the third-party software RecPack which is a kalman filter fitter. There are still some issues with the pull plots however it has been improved considerately and the bugs are understood. The main issue seems to be an underestimation of the error for low momentum values. See figures A.3, A.4, A.5, A.6, A.7, A.8.

Figure A.2 shows the current reconstruction efficiency, using simulated data in Baby MIND, defined as the number of reconstructed tracks from the number of identified trajectories and reconstructed with a momentum non-zero to remove errors in the code. For a single muon beam, the efficiency is more than 95% for the expected full range (0.2-10 GeV/c). Figure A.1 shows the current charge identification efficiency, which is defined as the number of tracks with the correctly assigned charge out of all the reconstructed trajectories. For a single muon beam, the efficiency is more than 95% above 0.8 GeV/c and above 80% in the region 0.2-0.8GeV/c.

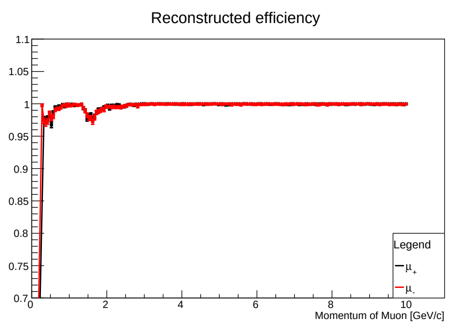



Figure A.1: Reconstruction efficiency for a single muon beam

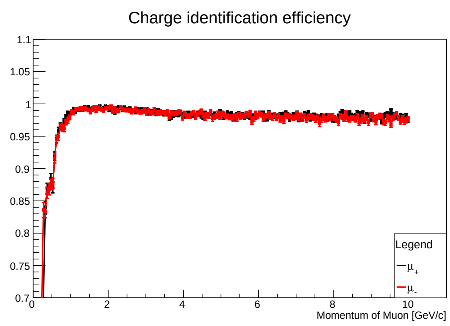



Figure A.2: Charge identification efficiency for a single muon beam

During June-July 2016 a test beam was performed to characterise the readout system, data

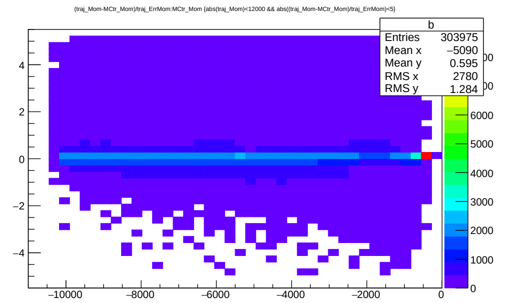



Figure A.3: Momentum pull plot for a single $\mu^-$ beam

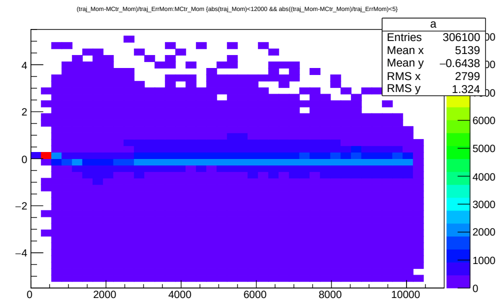



Figure A.4: Momentum pull plot for a single $\mu^+$ beam

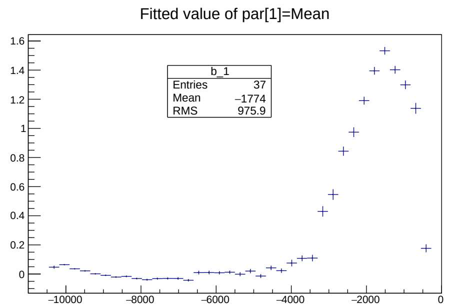



Figure A.5: The mean evolution of the pull plot for a single $\mu^-$ beam

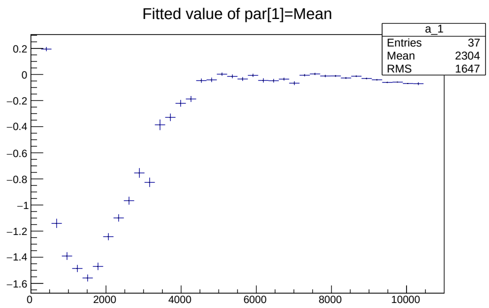



Figure A.6: The mean evolution of the pull plot for a single $\mu^+$ beam

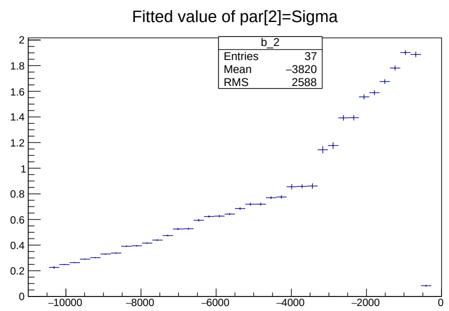



Figure A.7: The sigma evolution of the pull plot for a single $\mu^-$ beam

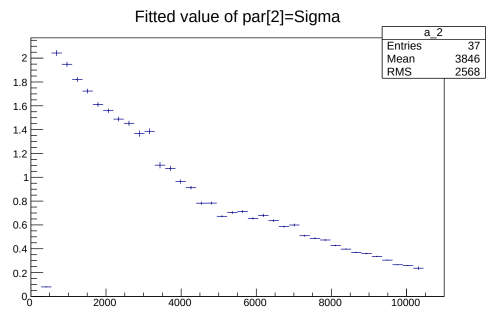



Figure A.8: The sigma evolution of the pull plot for a single $\mu^+$ beam

acquisition (DAQ) and electronics to be used in the Baby MIND detector. The test beam was at the T9 beam of the East Area, operating at the Proton Synchrotron (PS) at CERN. A Totally Active Scintillation Detector (TASD) A.9 constructed under the AIDA project (Advanced European Infrastructures for Detectors at Accelerators) was used to test the readout system, electronics, DAQ and reconstruction software. For the beam test, twelve planes, consisting of 16 scintillator bars $10 \times 10 \times 1000$ mm$^3$, read out on both sides by S12571-025C Hamamatsu MPPCs along alternating $x$ and $y$ directions were instrumented (a total of 384 MPPCs). The beam consisted of muons and pions from ~200 MeV/c up to 10 GeV/c. Figure A.9 shows a schematic of the TASD and figure A.10 shows the evolution of the beam profile as measured by the TASD during the test beam and reconstructed with the SaRoMan software.

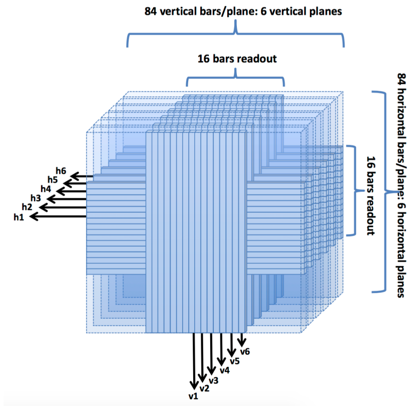



Figure A.9: The TASD with the instrumented bars visualised.

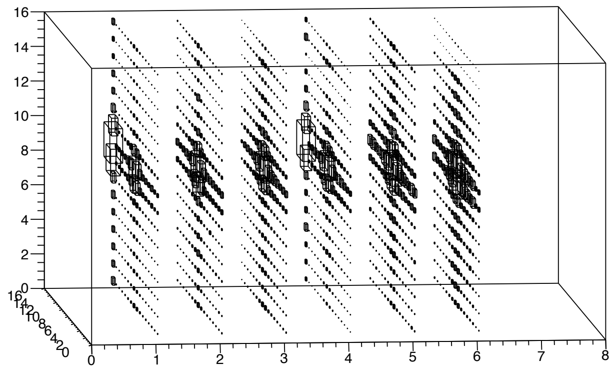


Figure A.10: Beam profile measured by the TASD.

Unfortunately for neutrino tracks it would be beneficial to perform simulations with the WAGASCI + Baby MIND but the WAGASCI design has not yet been shared from that collaboration. Instead these neutrino track simulations have been performed using the TASD as a target and then Baby MIND as a muon spectrometer behind it, see A.12 figure A.11. Also for visualization a sample event has been added. The efficiency plots provided,figures A.13 , A.14, A.15 and A.16, require more data to be fully understood, they do however look promising. Something which needs to be further understood is the pull plots which may indicate an issue for the momentum reconstruction, figures A.17 and A.18, to handle tracks which start off at an angle compared to the beam direction.

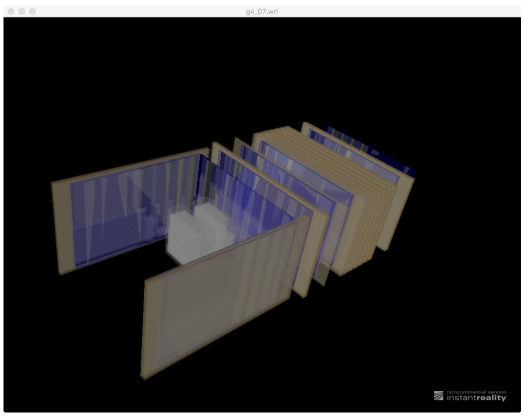


Figure A.11: A schematic for the TASD + babyMIND detector

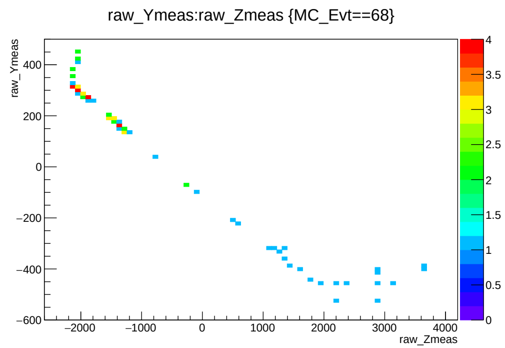



Figure A.12: Example of a $\mu^-$ CCQE event which interacts in the TASD shown in in Y-Z profile.

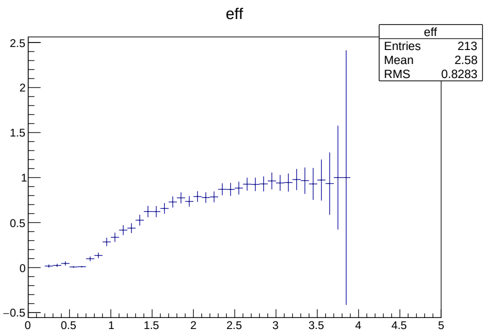



Figure A.13: Reconstruction efficiency for a single $\nu_\mu$ beam

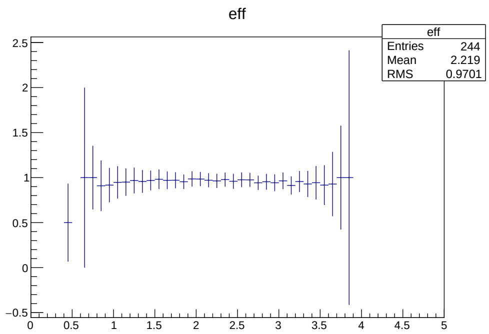



Figure A.14: Charge identification efficiency for a single $\nu_\mu$ beam

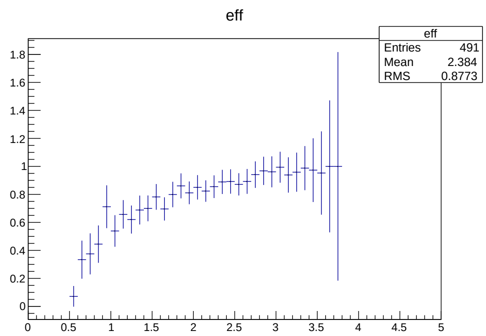



Figure A.15: Reconstruction efficiency for a single $\bar{\nu_\mu}$ beam

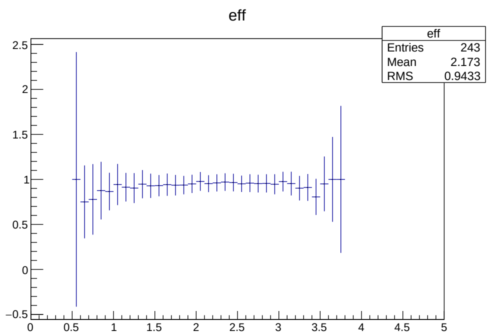



Figure A.16: Charge identification efficiency for a single $\bar{\nu_\mu}$ beam

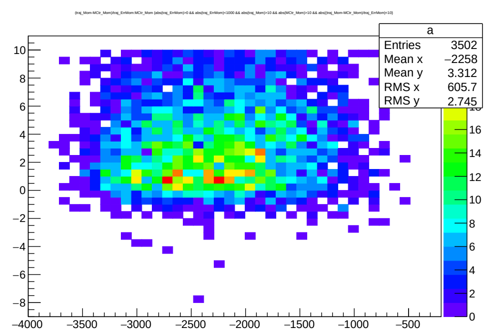



Figure A.17: Momentum pull plot for a single $\nu_\mu$ beam

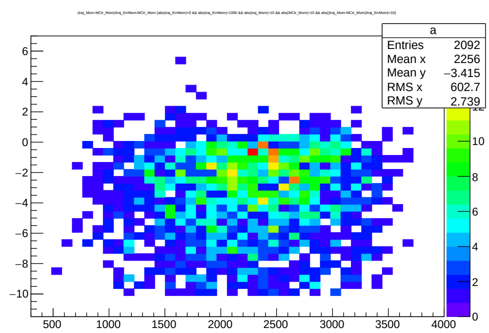



Figure A.18: Momentum pull plot for a single $\bar{\nu_\mu}$ beam

# Appendix B

# Presented last year

## B.1 Presented as Future work last year

### B.1.1 Software

The largest task is to improve the reconstruction algorithms to better classify the events and identify both the momentum and charge. Current results seem to show that the main issue is to choose the optimum hits when there is multiple occupancy.

This was improved and corrected in time for the testbeam performed in June of last year.

### B.1.2 Hardware

The electronics has been developed at the University of Geneva and will be tested at two test beams in June and July 2016. The current plan is to travel to CERN in June to perform tests with the electronics, to characterise the electronics in the laboratory and in the test beam and to emulate it in the digitization software.

This was tested and the digitization software confirmed with the acquisition of testbeam data.

### B.1.3 Physics performance

The main goal is to establish the performance of a MIND type detector in terms of position, angle, momentum and energy resolution and to characterise the particle identification and charge separation. Another goal is to benchmark MIND simulations and reconstruction algorithms and compare them with experimental results.

From previous MIND type detectors studies carried out in the context of the Neutrino Factory [46], charge current interactions are of the most interest for a MIND detector since they leave a clearer muon track. Reconstructions of electron tracks become more complex due to much shorter tracks and their similarity to hadronic showers. More detailed tests of electron beams will lead to further understanding of such events.

This is still ongoing. Neutrino tracks can be reconstructed in SaRoMaN, however many bugs have been discovered and have taken more time than expected.

### B.1.4 Neutrino interaction physics

The ultimate goal of the research is to characterise neutrino interactions in the WAGASCI detector, identified using Baby MIND to determine the expected cross-section ratio between CC events in water and in carbon.

This was not achieved and is still seen as a goal to be achieved in August when the detector will be shipped to Japan.

## B.2 Outline for the ”last” 12 months

### B.2.1 Software objectives

- Launch a complete version of the SaRoMaN software package by June 2016.
- Integrate the SaRoMaN and WAGASCI software packages by September 2016.

### B.2.2 Physics objectives

- Perform physics studies of non-standard neutrino interactions (NSI) by October 2016.
- Analysis of test beam at CERN by October 2016.
- Perform neutrino cross-section studies with WAGASCI by February 2017.
- Perform full Baby MIND beam tests characterization by June 2017.

### B.2.3 Hardware objectives

- Perform electronics Front End Board beam test at CERN by July 2016.
- Finalize Baby MIND by February 2017.

Most of these goals were achieved. SaRoMaN has been launched as a complete version and was launched on time. Unfortunately the WAGASCI collaboration has not shared their software so no integration has been made. NSI studies have not been conducted since unfortunately the collaboration with Durham has not been worked at. The electronics test beam and test beam analysis were performed on time. The full Baby MIND will be characterised this June and the design was finalised now in April 2017. Unfortunately neutrino cross-section studies with WAGASCI has not been started since the design has not been fully shared. However they were stated in January with another target design. Several bugs were discovered during these studies, this combined with time spend on other hardware related studies meant that the studies have not yet been completed but they will be completed by September 2017.

# Appendix C

# Outline for the next 12 months

## C.1 Objectives

### C.1.1 Software objectives

- Improve the SaRoMaN package reconstruction for Neutrino events by September 2017.

### C.1.2 Physics objectives

- Perform physics studies of non-standard neutrino interactions (NSI) by October 2017.
- Analysis of second test beam at CERN by October 2017.
- Perform neutrino cross-section studies with WAGASCI by December 2017.
- Perform neutrino cross-section studies with data from WAGASCI by March 2018.

## C.2 Future work

### C.2.1 Physics performance

The main goal is to establish the performance of a MIND type detector in terms of position, angle, momentum and energy resolution and to characterise the particle identification and charge separation. Another goal is to benchmark MIND simulations and reconstruction algorithms and compare them with experimental results.

From previous MIND type detectors studies carried out in the context of the Neutrino Factory [46], charge current interactions are of the most interest for a MIND detector since they leave a clearer muon track.

This is still ongoing. Neutrino tracks can be reconstructed in SaRoMaN, however many bugs have been discovered and have taken more time than expected.

### C.2.2 Neutrino interaction physics

The ultimate goal of the research is to characterise neutrino interactions in the WAGASCI detector, identified using Baby MIND to determine the expected cross-section ratio between CC events in water and in carbon.

## C.3 Gantt chart

Figure C.1 shows a combined chart of the timeline for Baby MIND and for what conferences I will be aiming for and where I will be. Combined with the objectives given in section C.1 provides a good plan and outline for the next 6 months.

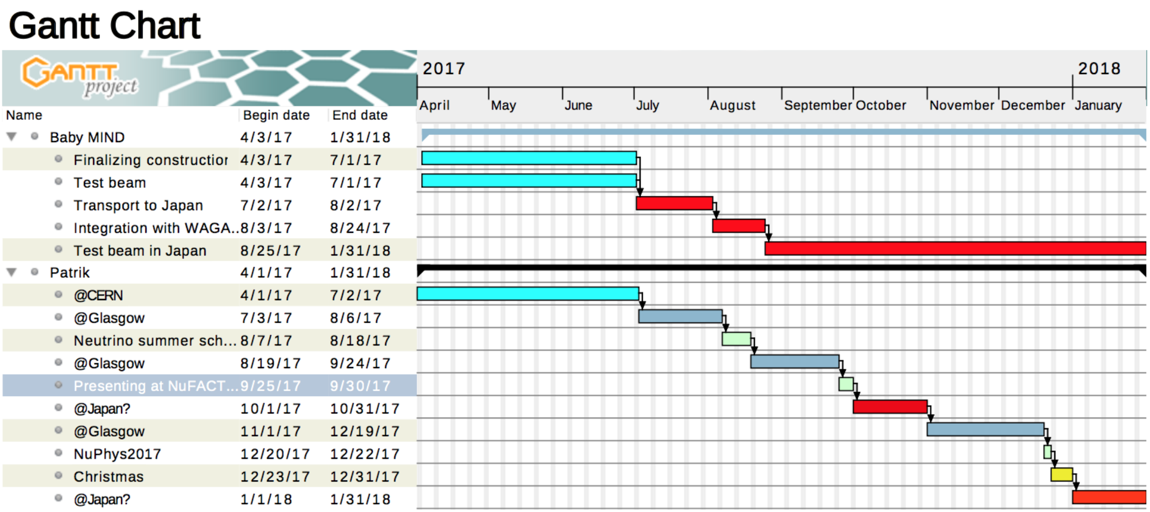



Figure C.1: A Gantt chart for the next 12 months.

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