Chapter 3

Neutrinos, Neutrino Detection and The Observed Raw Data

"I have done something very bad today by proposing a particle that cannot be detected, it is something no theorist should ever do."

— Wolfgang Pauli

3.1 Analysis Motivation

The story of neutrino physics starts from unexpected results from measurements of the energy spectrum of β decay in the early 20$^{\text{th}}$ Century. In the first section, I will go through a short overview of the theoretical background of light sterile neutrinos; why it is called "sterile neutrino" and why it is so often present in many theories describing phenomena beyond the Standard Model; and, finally, I will discuss how NOvA can look for sterile neutrinos.

3.1.1 Neutrino. A Brief History of a Unique Particle

As far as we know, the neutrino is a type of subatomic particle that cannot decay into further smaller constituents, and so is called a fundamental particle. Furthermore, unlike other fundamental particles, leptons and quarks, neutrinos are the only type of fermions that have neither electric nor color charges. Therefore, neutrinos can not feel the electromagnetic and strong interaction, but only gravity and the weak interaction. The weak interaction is aptly named. Its range is about 10^{-18} m, much less than an atomic nucleus diameter, for example 1.6 fm, or about 10^{-15} m for a proton in a hydrogen atom. On the other hand, neutrinos also have comparatively small masses, which are at least 6 orders of magnitude lighter than the masses of leptons and quarks. These observations make neutrinos almost impossible to detect. So, why would anyone have proposed the neutrino existence?

The Conundrum of the Continuous β Decay Spectrum

During the 1920s, nuclear physicists faced the dilemma of trusting energy conservation or not. This was caused by the unexpected continuous spectrum of β decay. β decay is a type of radioactive decay, in which an energetic electron or positron is emitted from an atomic nucleus. Therefore, the nucleus of atomic number Z is transformed from Z to Z+1 as a neutron is converted into a proton. Since the daughter atomic nucleus has slightly lower ground state energy than the parent atomic nucleus, the emitted electron or positron was expected to carry off the energy difference in kinetic energy form. However, the electron energy spectrum was measured to be continuous, and the electron to always carry off less energy than expected. Figure 3.1 shows a simple example of this process.

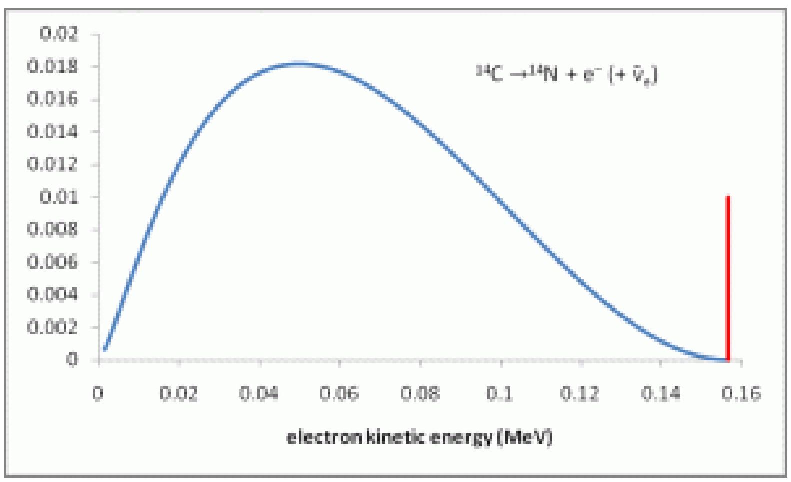

FIGURE 3.1: The decay ${}_6C^{14} \longrightarrow {}_7N^{14} + e^-$ is a good example to illustrate the continuous electron spectrum from β decay [2]. The blue line depicts the measured energy spectrum, which is dramatically different from the red line representing the originally expected energy of the emitted electron.

As it was shown in the above example, the electron energy is a continuous distribution instead of all electrons having a fixed energy value. Therefore, the energy conservation principle seemed not to hold at the atomic level, and this apparent violation of a fundamental law of Physics was not explained until Wolfgang Pauli wrote down his short but famous letter.

Pauli's Proposal

All the stories about neutrino physics, and for sure, the analysis presented in this dissertation started with the famous Pauli letter [3]. In late 1930, to defend the law of energy-momentum conservation, Wolfgang Pauli hypothesized that there is a light neutral particle of spin 1/2 also emitted from the atomic nucleus alongside the electron. Therefore, it can carry off the missing energy. However, this particle could not be detected by any known experimental methods at the time. As one of the greatest minds in the golden age of physics, Pauli's concern about neutrinos being forever undetectable was almost right. Pauli originally called his undetected neutral particle neutron. However, the name was used for the proton-like neutral hadron, discovered and named by James Chadwick in 1932. Enrico Fermi then renamed Pauli's neutral particle as neutrino, which means little neutral one in Italian [4].

The First Theory of β Decay

There remained the question of how the electron-neutrino pair was produced during a β decay process. By answering this question, Fermi made another fundamental contribution to neutrino physics (his first meaningful contribution being to give the neutrino a beautiful name):

$$n \longrightarrow p + e^- + \overline{\nu}_\mu \tag{3.1}$$

Let us follow Fermi's idea to write down his beautiful theory of the beta decay of nuclei [5]. The theory was built by an assumption that nuclei are bound states of neutrons and protons. Consider a simple quantum transition:

$$p \longrightarrow p + \gamma \tag{3.2}$$

The corresponding Hamiltonian has the form of the scalar product of the vector electromagnetic field and vector current:

$$\mathcal{H}^{EM}(x) = e\overline{p}(x)\gamma_\alpha p(x) A^\alpha(x) \tag{3.3}$$

By analogy with the above quantum transition electromagnetic Hamiltonian, Fermi hypothesized that the beta decay Hamiltonian was the scalar product of an electromagnetic vector current and a new vector current which was built by electron and neutrino fields, and their Hermitian conjugates:

$$\mathcal{H}^{\beta}(x) = G_F\overline{p}(x)\gamma^\alpha n(x)\overline{e}(x)\gamma_\alpha \nu(x) + h.c., \tag{3.4}$$

where G_F was named the Fermi constant.[1]

Based on the effective four-fermions Hamiltonian, Fermi calculated the spectrum of emitted electrons.

Happy to See You, Little Neutral One!

Soon after Fermi proposed his effective theory, Bethe and Peierls obtained the first estimate of the neutrino-nucleus cross-section [6]. Based on the result they obtained, Bethe and Peierls wrote down "there is no practically possible way of observing the neutrino". Indeed, after their paper, it was widely believed that the neutrino is an undetectable particle. Bruno Pontecorvo was the first physicist to challenge the opinion by proposing a radiochemical method of neutrino detection in 1946 [7][2].

Between 1953 and 1959, Frederick Reines and Clyde Cowan performed a series of experiments whose results are the first proof of the existence of the neutrino [9][3]. They detected antineutrinos produced in the Savannah River reactor from a β decay chain, by measuring the following process:

$$\overline{\nu} + p \longrightarrow e^+ + n \tag{3.5}$$

Their pioneering experiments also started the era of experiments using reactor neutrinos.

Different Types of Neutrino

Physicists had known four charged leptons, electron, muon, and their antiparticles, when they finally realized neutrinos are detectable.[4] Pushed by the uncontrollable impulse of finding new particles, two immediate questions spread out among particle physicists following the first experimental measurement of the neutrino, in fact, the antineutrino. They are:

- There is one neutrino that can be produced in association with an electron. Should there be another distinguishable neutrino that can be produced in association with a μ in β decay?
- The positron is the antiparticle for the electron. Should there be another distinguishable neutrino which is the antiparticle of the detected one?

[1] If we further compare the two Hamiltonians, we can find that the electromagnetic one is the Hamiltonian of the interaction of one boson field and two fermion fields, the beta decay one is the interaction of four-fermion fields. Therefore, the two constants, e and G_F, have different dimensions. Taking into account the charge, e, is a dimensionless quantity, the Fermi constant is then not, which means that the four-fermions Hamiltonian is an effective Hamiltonian.

[2] Pontecorvo suggested a Cl-Ar method, which is based on

$$\nu + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar\,.$$

This method was employed many years later to observe solar neutrinos in the first solar neutrino experiment [8].

[3] Reines and Cowan's pioneering experiments not only confirmed the Pauli-Fermi hypothesis but also proved the correctness of the V-A weak interaction theory by measuring the neutrino-nuclei cross-section.

[4] The third generation lepton, τ, was not predicted until 1971.

The first question was directly answered by π^+ decay. The two π^+ decay channels are:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \tag{3.6}$$

$$\pi^+ \longrightarrow e^+ + \nu_e \tag{3.7}$$

The ratio of the decay widths R can be defined as :

$$R = \frac{m_e^2(1 - \frac{m_e^2}{m_\pi^2})^2}{m_\mu^2(1 - \frac{m_\mu^2}{m_\pi^2})^2} \tag{3.8}$$

Plugging in values in the above equation, we find that R is about 1.2×10^{-4}, which means the second decay channel (Eq. 3.7) is strongly suppressed with respect to the first decay channel (Eq. 3.6). The Brookhaven neutrino experiment then produced a beam of high-energy neutrinos originating from decays of π^+ which are produced at accelerators[5]. The produced neutrinos then would be detected through one of these processes:

$$\nu + N \longrightarrow \mu^- + X \tag{3.9}$$

or

$$\nu + N \longrightarrow e^- + X \tag{3.10}$$

So, if the ν_e and ν_μ are the same particle, we expect to observe practically equal numbers of e and μ. However, in the Brookhaven experiment [10], 29 μs and 6 electrons were observed.

The second question, in fact, was answered first through the inverse β decay process first proposed by Pontecorvo as introduced above:

$$\nu + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar \tag{3.11}$$

Between 1955 – 1960 (just a little bit later than Reines and Cowan's series of experiments), Ray Davis studied the above process by employing reactor antineutrinos from the Brookhaven reactor as the source, and carbon tetrachloride as the target. His results showed that the probability of Chlorine-37 to convert to Argon-37 reaction was no more than 10%. The reason is that, based on the law of lepton number conservation[6], this reaction needs to involve a neutrino (not an antineutrino if they are not identical). Beta decay, on the other hand, needs to involve an antineutrino due to the process requiring an antilepton to balance

[5]This is also the experiment that started the era of experiments with accelerator neutrinos.

[6]The law of lepton number conservation says that the difference between the total number of leptons and the total number of antileptons is always a constant.

the electron. Therefore, reactor neutrinos can only convert chlorine-37 to argon-37 when neutrinos and antineutrinos are identical. This great work not only proved an electron neutrino has its own distinguishable antiparticle but also proved that the weak interaction process obeys the law of lepton number conservation.

Neutrino and Discovery of the Neutral Current Weak Interaction

At the early 1970s, the Glashow-Weinberg-Salam theory was just thought as one of many possibilities to explain particle interactions, until the neutral-current (NC) neutrino interaction was discovered in Gargamelle, a liquid bubble chamber detector operating at CERN. The discovery of the NC interaction was the first proof that electromagnetic and weak interactions are a unified theory.

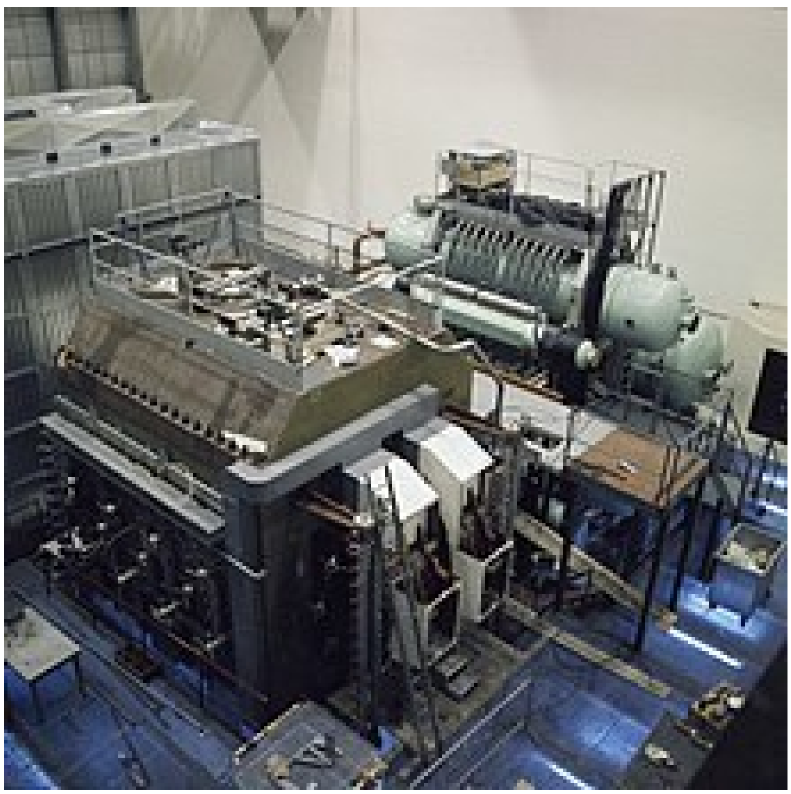

FIGURE 3.2: The Gargamelle heavy bubble chamber detector (4.8 m long, 2 m in diameter) is filled with 18 tonnes of liquid Freon. The Neutral-Current interaction was first observed in it in 1973 at CERN [11].

Neutrinos can interact via charged-current (CC) processes, for instance, The neutrino-quark CC interaction, by exchanging a W-boson, is represented by the inclusive process:

$$\nu_\mu + N \longrightarrow \mu^- + X \tag{3.12}$$

where X means any possible hadrons. The corresponding effective Hamiltonian is

$$\mathcal{H}^{CC} = \frac{G_F}{\sqrt{2}} 2\overline{\mu}_L \gamma^\alpha \overline{\nu}_{\mu L} j_\alpha^{CC} + h.c. \tag{3.13}$$

If in addition, neutrino and quarks can also interact via NC by exchanging a Z-boson, such as:

$$\nu_\mu + N \longrightarrow \nu_\mu + X \tag{3.14}$$

We then can find only hadronic final states. The corresponding effective Hamiltonian is

$$\mathcal{H}^{NC} = \frac{G_F}{\sqrt{2}} 2\overline{\nu}_{\mu L} \gamma^\alpha \nu_{\mu L} j_\alpha^{NC} + h.c. \tag{3.15}$$

Comparing the above two effective Hamiltonians, we see these interactions are both characterized by the Fermi constant. Therefore, the cross-section of these two processes is comparable.

The first NC event was observed at the beginning of 1973, and motivated exhaustive searches for hadronic NC-induced interactions.

What They Knew!

- In 1954, Zhengning Yang and Robert Mills extended the gauge theory for abelian groups to non-abelian groups to explain strong interactions.
- In the late 1950s, the symmetry breaking concept was proposed in superconductivity studies.
- In 1960, Yoichiro Nambu discussed the application of symmetry breaking in particle physics.
- In 1961, Sheldon Glashow ‘merged‘ the weak force and electromagnetic interaction.
- In 1964, three independent groups proposed the mass generation theory without "breaking" gauge theory.[7]
- In 1967, Abdus Salam and Steven Weinberg incorporated the Higgs mechanism into the electroweak interaction, to give rise to the masses of electroweak interaction fundamental particles. The Glashow-Weinberg-Salam model was widely accepted from the moment the weak neutral-current interaction mediated by Z boson exchange were observed.
- In 1973, asymptotic freedom was proposed by two independent groups.[8]
- In 1983, the charged and neutral bosons of the weak interaction were discovered experimentally.
- In 1995, the top quark was measured in CDF and DØ.

[7] The three independent groups are: 1) Peter Higgs; 2) Gerald Guralnik, C. R. Hagen, and Tom Kibble; 3) Robert Brout and François Englert

[8] The two groups are: 1) David Politzer; 2) David Gross and Frank Wilczek. They proposed the theory in the same year.

- In 2000, the tau neutrino was observed by DONUT [12].
- In 2012, the Higgs Boson was finally discovered at the LHC.

After 'merging' the above theoretical proposals and experimental discoveries, physicists around the world developed the Standard Model of Particles in stages. The theory can explain three of the four known fundamental interactions and has had great successes in producing experimental predictions.

The Standard Model seemed to be the FINAL THEORY physicists were looking for, BUT ...

3.1.2 Neutrinos in the Standard Model and Beyond

Over the past 45 years, the Standard Model of Particle has been a hugely successful theory. It provides an excellent description of almost all of the phenomena in particle physics. The only sector of this effective model which can not stand up to experimental examination is its assumption of massless neutrinos. The atmospheric neutrino oscillation discovery, SuperK [13] and SNO [14], is one of few significant recent discoveries in particle physics. The oscillation phenomenon was then also proved by solar experiments (Homestake [8], Gallex [15], SAGE[15]), and the reactor experiment KamLAND [16]. The experimental discovery of the neutrino flavor-changing phenomenon not only proves the neutrinos are not massless particles, but also explained the long-standing solar neutrino problem. The phenomenon caused immediate great experimental and theoretical interest, though Bruno Pontecorvo has first proposed it in 1957. The precise measurement of neutrino oscillation can shed light on several fundamental properties. A couple of neutrino experiments, based on the different type of neutrino sources, have been built to contribute to this field[9]. We begin this section by shortly introducing the Standard Model and its building pieces. We then discuss neutrino properties in the Standard Model circa 1970s and explain how neutrino physics has developed into its current form, driven by both experimental discoveries and theoretical motivation for neutrino mass generation in the last decades.

The Standard Model of Particle Physics

The Standard Model (SM), our current best theory, is a type of periodic table of the particle physics. Instead of listing the chemical elements, the SM lists the two types of the fundamental particles, who can not be broken down into smaller particles, and make up the atoms. The two kinds of matter particles are: 1) hadrons, which can interact by the strong force, 2) leptons, which can not feel the strong force. The most well-known SM particle is the electron, which has a negative electrical charge and can be detected by electromagnetic interaction. On the other hand, neutrinos are the most mysterious piece, due to the fact that they do not carry electrical charge.

[9] The following experiments dominate the precise measurement of neutrino oscillations in the last ten years. They are: 1) BOREXINO [17], a solar neutrino experiment; 2) MINOS [18], K2K [19], and T2K [20], long-baseline accelerator neutrino experiments; and 3) Daya Bay [21], RENO [22] and Double Chooz [23], reactor neutrino experiments.

Standard Model Particles and Their Interactions

The building pieces of the SM are shown in Fig. 3.3. The SM particles can also be classified into fermions, who are spin-1/2 particles, and bosons which are integer-spin (0 or 1) particles. The total 12 fermions are the fundamental constituents of matter, and they can be further classified into two groups, leptons and quarks. Each fermion group consists of three generations, which can be identified by their masses.

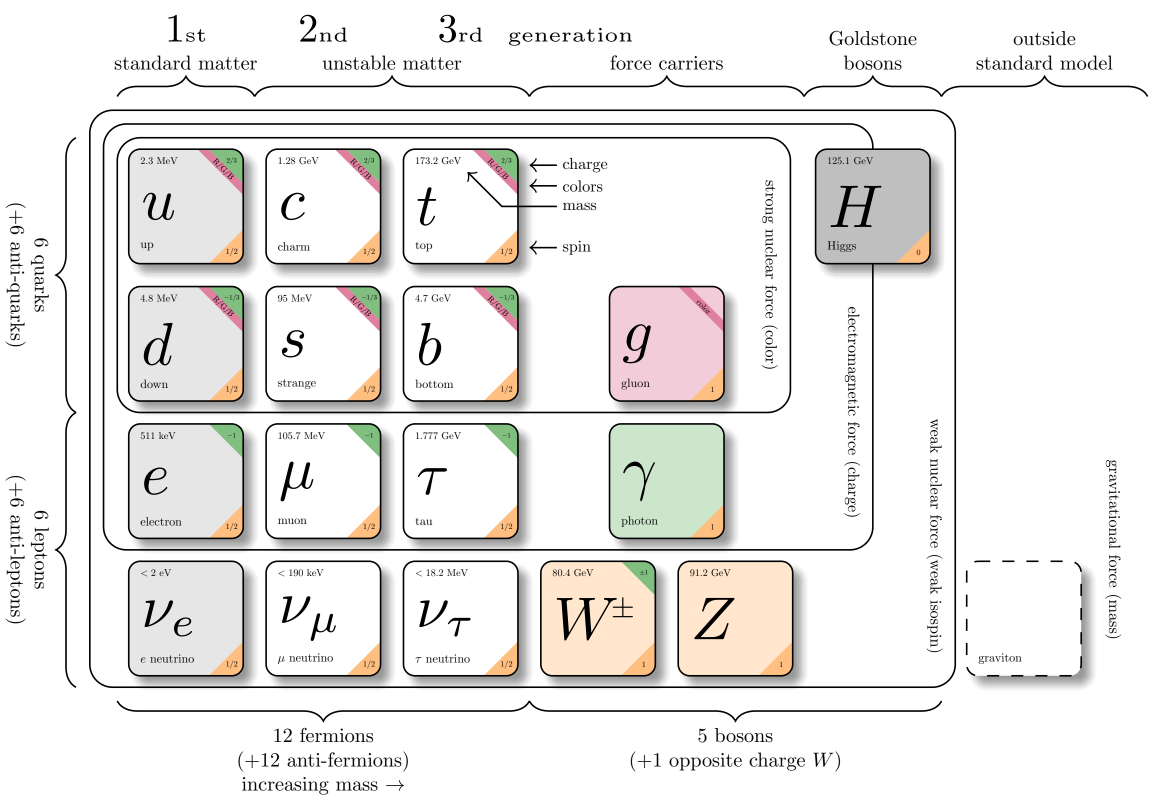

FIGURE 3.3: The Standard Model Particles. The plot was produced by David Galbraith and Carsten Burgard at the CERN Webfest 2012.

Besides fermions, there are four types of bosons, whose spin is 1, which are the mediators of the strong (eight gluons), weak (Z^0 and $W^{\pm}$), and electromagnetic (γ) interactions, respectively. The Higgs boson (spin 0) is the last discovered SM particle which is predicted by the electroweak theory, and is responsible for giving massive particles, including itself, their masses.

The three types of SM fundamental interactions are listed in Fig.3.4.

- Weak Interaction: almost all SM particles (Z^0 and $W^{\pm}$ bosons and all fermions) carry the weak charge, and, therefore, experience the weak interaction, whose interaction range is about 10^{18} meters, which is approximately 0.1% of the diameter of a proton.

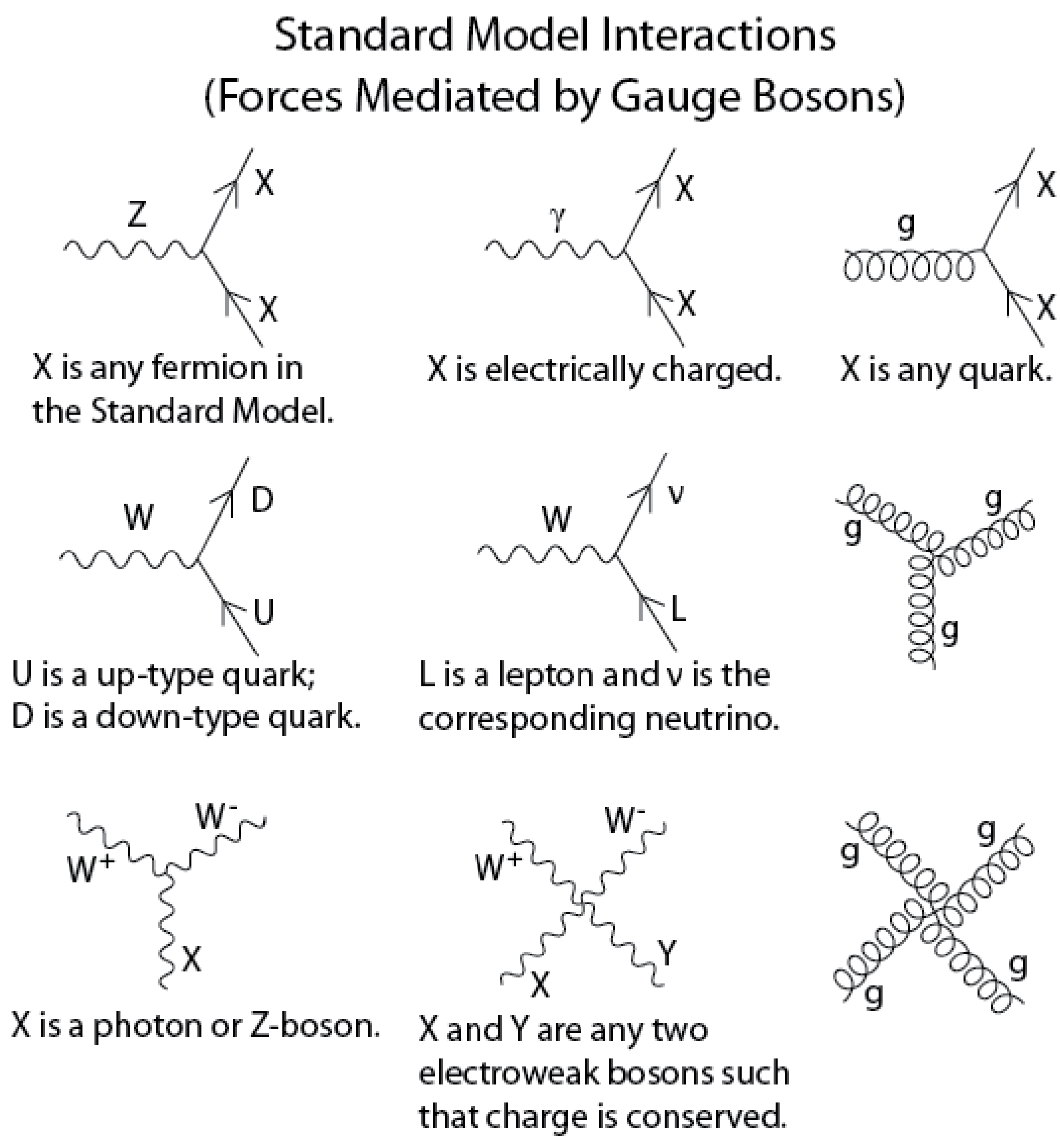

FIGURE 3.4: Standard Model Interaction Feynman diagrams. These interactions form the basis of the Standard Model Interactions [24].

- Strong Interaction: only quarks and gluons carry the color charge, and therefore only they can experience the strong interaction, whose interaction range is about 10^{15} meters, which is approximately the diameter of a medium-sized nucleus.
- Electromagnetic interaction: is experienced by SM particles which have a non-zero electric charge, is a force of infinite range which follows the inverse-square law, and therefore can hold atoms together.

The Only Massless Matter Particles in the Standard Model

Before physicists finally realized the parity-violating nature of weak interaction and its relation with neutrino mass, it was firmly believed that neutrinos must have zero mass due to it being interwoven into the weak interactions. The other massless particles, gluons and photon, are force carriers, not matter particles.

In the SM Lagrangian, the only way to construct a Dirac mass term for fermions is :

$$-\mathcal{L}_{mass} = m(\overline{\psi}_L \psi_R + \psi_L \overline{\psi}_R) \tag{3.16}$$

Due to the absence of the right-hand neutrino and the left-hand antineutrino, the Dirac mass term could not be constructed in the SM framework.

Neutrino Oscillation as a Window to New Physics

Bruno Pontecorvo first introduced the idea of neutrino oscillation in 1957. Neutrino oscillation evidence was accumulated from the observation of solar and atmospheric experiments over the years[10]. The flavor-changing phenomenon is a direct proof of massive neutrinos, which are not included in the SM.

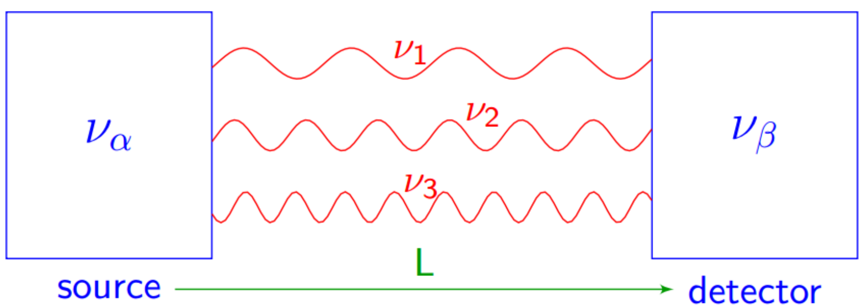

FIGURE 3.5: Three-Flavor Neutrino Model Oscillation. The neutrino flavor changes after it travels for some distance. Plot taken from Stefano Gariazzo's talk.

3.1.3 The $\overline{\nu}_e$ Appearance Anomaly

While the three-flavor neutrino model is well established, there are several oscillation results that cannot be interpreted based on it. However, they could be explained by the introduction of extra neutrinos [25]. The first experimental result supporting the possibility of extra neutrino species came from the Liquid Scintillator Neutrino Detector (LSND) experiment [26].

[10] The SNO and SuperK results play a decisive role in neutrino oscillation discovery.

The LSND Signal

LSND [27], is a single-detector experiment, designed for two purposes: 1) search for $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$ oscillation; 2) measure neutrino-nuclear cross-sections. The $\overline{\nu}_\mu$ travels 30 m to arrive at the detector.

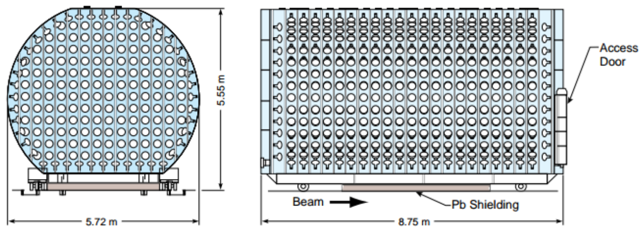

FIGURE 3.6: A schematic drawing of the LSND detector. Plot taken from the LSND public plots webpage [27].

The LSND released result, displayed in Fig. 3.7, shows a total excess of beam events with final-state electrons of $87.9 \pm 22.4 \pm 6.0$ ν_e candidates events with a background estimated at 30 ± 6.0 events. The simplest interpretation of this excess in terms of neutrino oscillations requires a new mass splitting of about 1 eV^2, three orders of magnitude larger than the atmospheric mass splitting Δm^2_{atm}, which would be the largest neutrino mass splitting measured to date.

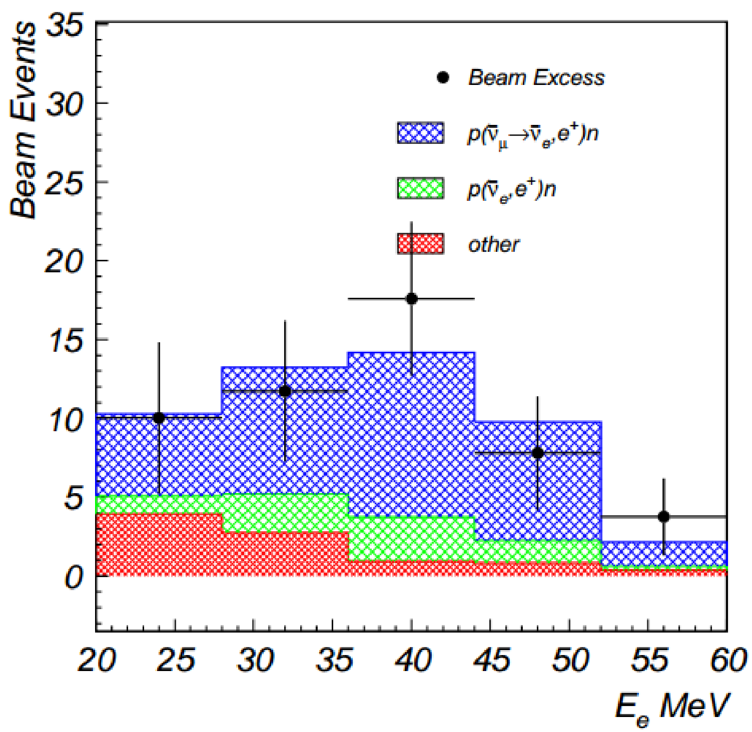

FIGURE 3.7: The LSND energy distribution for events. Plot taken from LSND public plots webpage [27].

The KARMEN Constraint

The KARMEN experiment has a very similar experimental setup to LSND, and was designed to check the puzzling LSND results. KARMEN measured 15 events which survived the analysis selection cuts. The KARMEN results rule out a significant portion of the LSND oscillation allowed region with $\Delta m^2 > 10eV^2$, as shown in Fig. 3.8.

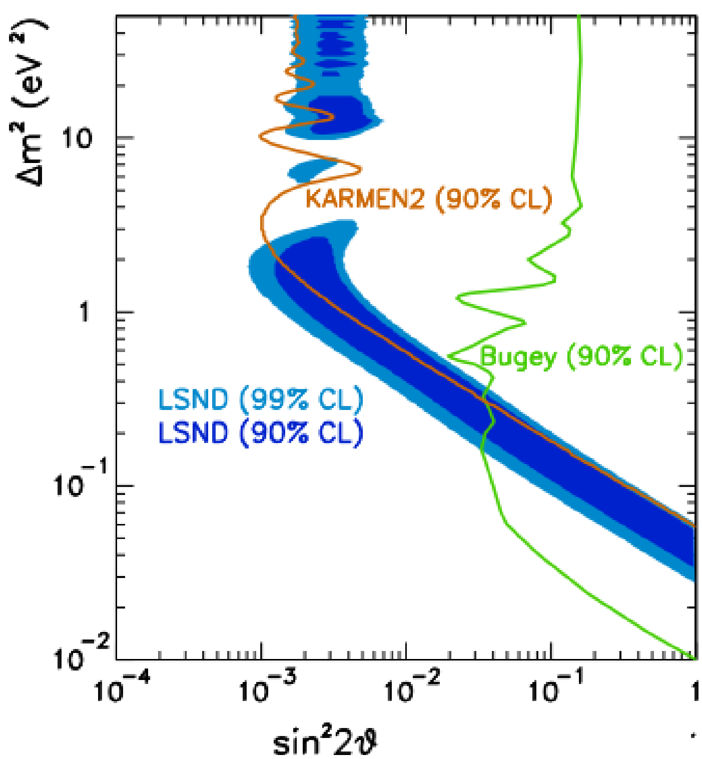

FIGURE 3.8: The $(sin^2 2\theta, \Delta m^2)$ oscillation parameter fit for the LSND, Bugey, and KARMEN [28].

The MiniBooNE ν_e and $\overline{\nu}_e$ Appearance Searches

The MiniBooNE experiment, which was another experiment designed to test LSND, has reported oscillation results in both neutrino and antineutrino mode. Both results show a low-energy excess in a region not directly compatible with LSND, but the most recent paper claims to be consistent with and verify the LSND signal [29].

3.1.4 What We Know?

We know there is no mass generation mechanism inside the SM; we know the LSND appearance anomaly cannot be explained within the three-flavor neutrino model, but it can be explained by an additional light sterile neutrino; and we know that a right-hand neutrino can fulfill the SM mass generation mechanism, but it should be much heavier than the one needed to explain the LSND results.