Measurement of Neutron Multiplicity from Neutrino Interactions

at Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

by

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ABSTRACT

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26-ton, gadolinium-doped water Cherenkov detector located on the Booster Neutrino Beamline (BNB) at Fermilab. ANNIE's primary physics objectives include measuring neutron multiplicity for neutrino-nucleus interactions and performing cross-section measurements of Charge Current Quasi-Elastic (CCQE) and Neutral Current Quasi-Elastic (NCQE) processes. These measurements aim to improve neutrino energy reconstruction and reduce uncertainties in current and future neutrino oscillation experiments. Additionally, ANNIE serves as a testbed for advanced technologies such as Large Area Picosecond Photodetectors (LAPPDs) and Water-Based Liquid Scintillator, which enhance vertex resolution and enable detection below the Cherenkov threshold. The objective of this PhD research is to conduct a measurement of neutron multiplicity from neutrino interactions using PMTs and LAPPDs, incorporating all experimental upgrades to minimize uncertainties in neutron count measurements in ANNIE. Furthermore, the research aims to contribute to the improvement of neutrino interaction simulations, benefiting both current and future neutrino experiments.

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Chapter 1

INTRODUCTION

1.1 Neutrino Physics

In 1930, W. Pauli postulated the existence of a massless particle, later named the neutrino, to account for the conservation of energy and momentum in beta decay [1]. Enrico Fermi subsequently developed the theoretical framework for neutrinos [2]. However, detecting neutrinos proved to be a significant challenge due to their weak interactions with matter. The first experimental detection of the electron neutrino was accomplished by Cowan and Reines in 1956 [3]. In 1962, Lederman and his colleagues discovered the muon neutrino [4], confirming the existence of different neutrino flavors. The tau neutrino was first directly observed in 2000 by DONUT collaboration at Fermilab [5]. Today, we recognize three neutrino flavors—electron, muon, and tau neutrinos—along with their corresponding antiparticles.

Over the years, various properties of neutrinos have been uncovered, including the phenomenon of neutrino oscillation, which demonstrates that at least two neutrino mass eigenstates are nonzero. Neutrino oscillation refer to the quantum mechanical process that describes how neutrinos change flavor as they travel through spacetime. The probability of the neutrino flavor change is characterized by a set of parameters such as the squared mass differences Δm^2_{ij}, the neutrino energy E, CP-violation phase δ_{CP}, and the distance traveled L by neutrino flavors.

Since the discovery of neutrino oscillations, experimental efforts have focused on reducing systematic uncertainties in oscillation parameters, determining the neutrino mass hierarchy, improving neutrino energy reconstruction, understanding absolute neutrino mass, and investigating CP violation in nature.

Despite advancements, certain experimental limitations remain, as seen in experiments like MINERvA [6, 7], NOvA [8], and T2K [9], where neutrino interactions simulation does not agree with data due to overestimation of neutron candidates from the neutrino interactions. This limitation affects the precision of neutrino oscillation studies and energy reconstruction. The ANNIE experiment has the potential to provide critical inputs to improve the simulations, contributing to the success of current and future experiments.

1.2 Acceleration Neutrino Neutron Interaction Experiment (ANNIE)

1.2.1 *The ANNIE Detector*

The ANNIE detector, illustrated in Figure 1.1, consists of a cylindrical steel water tank with a radius of approximately 1.5 m and a height of about 4 m, housing 26 tons of gadolinium-loaded water. The water is enriched with 0.2% gadolinium sulfate ($Gd_2(SO_4)_3$). Gadolinium (Gd) captures thermalized neutrons within approximately 30 μs, which is ten times faster than pure water. Additionally, the gamma signature of 8 MeV associated with Gd is four times higher energy than that of pure water. These characteristics significantly enhance the neutron detection efficiency of the detector compared to using pure water.

The detector has 114 photomultiplier tubes (PMTs) of various types, including 10-inch Hamamatsu type (blue and grey), 11-inch High-Quantum-Efficiency (red on top), and 8-inch Hamamatsu PMTs (red on side wall) arranged around the inside surface of the tank as shown in Figure 1.2. The detector can accommodate multiple LAPPDs along with the PMTs to detect emission of cherenkov light, produced when charged particles generated in the interactions exceed their Cherenkov energy threshold.

LAPPDs feature a 20 × 20 cm^2 active area with a thickness of less than 1 cm. These LAPPDs achieve a transit time resolution of approximately 100 ps and a position resolution of 1 cm, whereas PMTs typically provide only a transit time resolution of about 1 ns and no position information within the PMT [10]. Thanks to the fast timing, using LAPPDs to supplement PMTs provides significant improvements in event reconstruction. ANNIE's simulations indicate that even a limited number of LAPPDs can substantially improve directional and vertex reconstruction, particularly for muon vertices. With three LAPPDs currently deployed within the ANNIE tank, preliminary results have demonstrated successful neutrino detection using these advanced photon detectors.

The Booster Neutrino Beam (BNB), located approximately 110 meters upstream of the ANNIE experiment, primarily consists of muon neutrinos. In ANNIE, for the Charge Current (CC) interactions, a neutrino interacts with a nucleus and produces a corresponding lepton and hadrons. Since the interacting neutrino is a muon neutrino, the resulting lepton is a muon. If resulting hadron is a neutron, it captures on either Gd or water, produces gamma-ray cascades along with heavier isotopes (gadolinium or deuterium, respectively), where gamma-rays are subsequently detected by the tank's PMTs and LAPPDs, and most muons travel a considerable distance outside the tank before stopping, preventing full deposition of their kinetic energy within the tank.

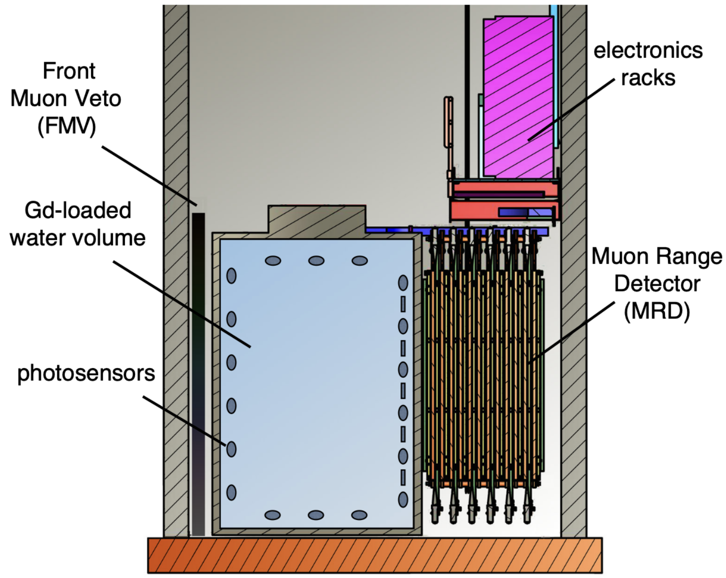

Figure 1.1: An overview of ANNIE experiment setup along with FMV, PMT, MRD, and electronics racks in [11].

To estimate energy of these muons, the experiment includes a Muon Range Detector (MRD) located downstream of the tank. The MRD consists of six vertical and five horizontal layers of scintillator paddles, each measuring 15–20 cm wide and 150 cm long, connected to PMTs for signal readouts. The scintillation signals are used to reconstruct the muon vertex and propagation angle by analyzing the muon track's position and timing data recorded in the MRD.

Finally, two layers of scintillator paddles, known as the Front Muon Veto (FMV), are connected to 2-inch PMTs for signal readout and installed upstream of the tank. The FMV identifies muons produced from neutrino interactions occurring upstream of the tank. These muons are classified as beam-induced neutrino backgrounds, as they originate outside the tank's interaction volume.

1.2.2 *Data Acquisition and Trigger system*

The Data Acquisition (DAQ) system in ANNIE enables each detector subsystem described in 1.2.1 to independently collect data based on its specific triggers. PMT waveforms are digitized using VME modules, while the TDC assigns time stamps to the triggers from all subsystems. The Central Trigger Card (CTC) coordinates various triggers from the VME and ADC electronics. All triggers operate independently and do not rely on one another. Post-acquisition, the CTC uses time stamps to synchronize the information from all subsystems, generating raw data files for different types of events. The processes of DAQ is developed based on ToolDAQ framework

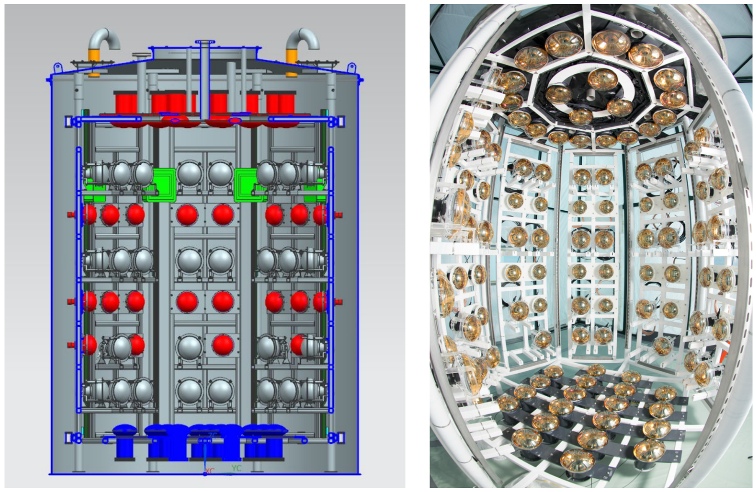

Figure 1.2: The left side of figure presents a 3D display showcasing the various types of PMTs in different colors, while the right side features the actual ANNIE tank with all PMTs mounted [10].

by B. Richards [12]. Due to certain limitations in DAQ system, the VME can record particular events in various time windows. When the BNB beam is on, VME collects data for 2 μs in the prompt window for all neutrino interaction events. If the deposited charge on the PMTs exceeds a threshold of 5 photoelectrons (p.e.), the extended-window trigger extends the data collection period to 70 μs, covering the delayed window (2 μs - 70 μs). This configuration is to collect data for CCQE signal events. Additionally, if no trigger is detected after every 200 clock-ticks (1.6 μs), the system activates a frequency-based trigger (minimum-bias trigger) to collect data for NCQE signal events. Otherwise, any data collected within the first 2 μs consider to be beam correlated background events. When BNB beam is off, if a cosmic muon was detected on the first and last plate of the MRD, DAQ will collect data for the 70 μs in the beam-off trigger mode. There are also self-triggers for specific calibration events, such as LED, laser, and Americium-Beryllium (AmBe) sources. The data collection windows for these triggers are 2 μs for LED and laser calibration and 70 μs for AmBe calibration.

The standalone LAPPD system, consisting of the LAPPD and its electronics as shown in Figure 2.3, its power supply and data collection from LAPPDs controlled by the external breakout box. This breakout box manages power distribution and signal interfacing with the ANNIE Central Card (ACC), which then communicates with the main DAQ system.

1.2.3 *Physics goals of ANNIE*

ANNIE's primary physics objectives include measuring neutron yield for neutrino-nucleus interactions and performing cross-section measurements of CCQE and NCQE processes. In the neutrino nucleus interactions, when neutrinos interact with nuclei in the gadolinium-loaded water, they emit neutrons. The number of neutrons emitted depends on the specific interaction that occurs. The process of quantifying the number of neutrons is referred to as neutron multiplicity. We will measure neutron multiplicity from neutrino interactions as a function of lepton kinematics and its angular distribution. The final-state neutron multiplicity measurement for the neutrino interactions is an important component to improve neutrino nucleus interaction models. Additionally, understanding neutron multiplicity plays an important role in reducing systematic uncertainties in neutrino oscillation measurements.

In ANNIE, the primary focus is to determine the neutron multiplicity for CC interaction processes. In this process, neutrino interactions result in muons and hadrons as final-state products. To identify whether a specific event corresponds to a CC interaction and whether the final-state hadrons includes neutrons that should be included in the neutron multiplicity analysis, the following criteria should be considered:

- The muon should be observed by the MRD, which helps determining the reconstruction of muon energy and angle.
- LAPPDs are then used to reconstruct the neutrino interaction vertex.
- Any neutrons would thermalize and emit light via gamma cascade process, which is then detected by PMTs.

ANNIE also aims to study cross-sections for CCQE and NCQE processes as a function of lepton kinematics and its angular distribution.

1.2.4 *Simulation*

Monte Carlo (MC) simulations are an essential component of any physics study, providing critical insight into expected results under experimental conditions. The ANNIE experiment employs two primary simulation frameworks: GENIE [13] and WCSim [14, 15]. GENIE, a neutrino event generator based on ROOT framework [16], models neutrino-nucleon interactions using BNB flux files and ANNIE's detector geometry. Developed by group of neutrino physics personnel, GENIE is widely adopted in neutrino physics experiments due to its superior performance and customizable features tailored to individual experimental needs. Following the interaction simulation in GENIE, the final-state particles are processed in WCSim, a Water Cherenkov detector simulation built on the GEANT-4 framework [17]. WCSim generates raw data samples for various types of events, making it convenient to simulate different kind of events such as signal events, background contributions from surrounding rock, and cosmic ray interactions. Together, these tools enable ANNIE to create targeted datasets for optimizing analyses and validating experimental results.

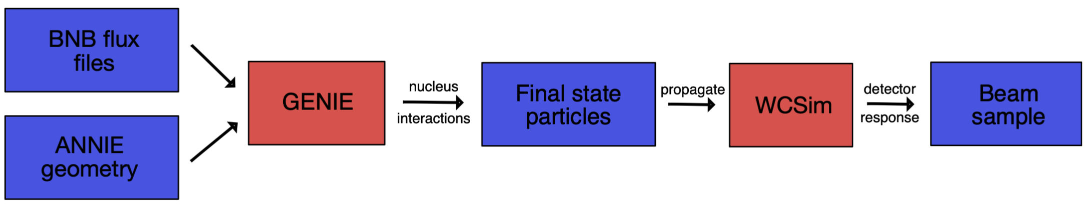

Figure 1.3: Flowchart of simulation in ANNIE [10].

1.2.5 *Detector calibration*

Detector calibration is essential for ensuring the reliability of the detector system and for enabling accurate analysis of detector data. In the ANNIE experiment, various calibration techniques are utilized to optimize detector performance. One such technique is the AmBe calibration. It employs an AmBe neutron source to characterize the detector's response to neutrons. The AmBe source emits neutrons that interact with the Gd-water in the tank, producing gamma rays upon neutron capture. These emitted gamma rays are then analyzed to assess the detector's efficiency and timing resolution for neutron detection at different locations inside the tank.

The LED calibration is used to assess the photodetectors (PMTs and LAPPDs) gains. For each individual photodetector, the amplification factor for the single photoelectron (PE) response varies with its gain. To determine the gain of each photodetector, LED calibration is employed to measure the single PE response at a specific supply voltage. Accurate timing information is essential for the reconstruction of the muon vertex inside the tank. The laser calibration is used to determine the precise time response of photon detection on PMTs and LAPPDs. Additionally, there are other calibration efforts for determining the MRD and FMV efficiency, and Gd-water transparency within the detector.

Chapter 2

CURRENT WORK

2.1 Beam-correlated Neutron Background studies

As mentioned earlier, the ANNIE detector is positioned approximately 100 meters downstream of the BNB's interaction target. Each beam spill consists of 84 proton bunches, with a total spill duration of 1.6 μs. On average, each spill delivers around 5×10^{12} protons-on-target (POT). The resulting neutrino beam is highly enriched in muon neutrinos (ν_μ), comprising roughly 93% of the beam's composition, with an energy spectrum peaking at approximately 800 MeV [18].

As discussed in 1.2.3, a significant portion of the neutrino's energy in neutrino-nucleus interactions is carried by final-state neutrons. Measuring neutron yield enhances our understanding of neutrino interactions and provides critical feedback for improving neutrino energy reconstruction. Furthermore, improved neutrino energy reconstruction offers essential inputs to refine neutrino oscillation studies and reduces systematic uncertainties for current and future long-baseline experiments.

In ANNIE, final-state neutrons can travel approximately 1 meter before thermalizing and being captured in the detector. Neutrons captured inside the tank not associated with beam-induced neutrino interactions are considered potential background candidates. These neutrons may arise from particle interactions in the dirt behind the detector. Topologically these beam correlated background neutrons and beam-induced neutrons from neutrino interactions are similar, making it particularly challenging to distinguish between background and signal neutrons.

My current work focuses on determining the beam-correlated neutron background for ANNIE. Here, two types of backgrounds are considered: constant-in-time (CIT) and beam-induced (BI) backgrounds.

- **CIT Background:**

  This arises from the natural radioactivity present in materials surrounding the detector. A large fraction of CIT can be omitted by having 2 μs prompt window around the arrival of the beam spill of neutrinos for the analysis. Beam-off data provides a reliable estimate of the CIT background, as it eliminates concerns about beam-induced neutron signals.

- **BI Background:**

  BI backgrounds dominate in the 2–70 μs delayed window and primarily include two sources: skyshine and dirt neutrons. Skyshine neutrons are secondary particles generated in the beam dump. These neutrons scatter in the atmosphere and, after undergoing multiple interactions, eventually reach the detector. Dirt neutrons, on the other hand, are produced upstream of the tank by neutrino interactions in the surrounding soil.

To ensure that the analysis focuses on beam-correlated neutron backgrounds in the tank, any triggering event detected by the FMV, such as muon detection, is eliminated. The remaining interactions are assumed to occur within the tank. Among these events, the neutron rate must be determined for neutrons potentially originating from neutrino interactions with upstream rock or neutrino-nucleus interactions occurring outside the tank. Additionally, events with muon tracks in the MRD are omitted, as these are more likely to represent actual neutrino events rather than background.

Furthermore, identifying neutron candidates is crucial. In ANNIE, neutrons are primarily captured on gadolinium, emitting a gamma cascade of five photons on average. These gamma rays are typically detected by 10–20 PMTs, with a deposited charge ranging between 10–40 p.e. Due to the relatively small size of the detector compared to other Cherenkov detectors, neutron signals are less prominent than high-energy electron and muon signals, making it challenging to distinguish them from dark noise and afterpulses. To address this, an AmBe calibration campaign was conducted, resulting in the establishment of the following selection criteria to isolate pure neutron signals and minimize mimicking signatures:

$$Q_{tot} \leq 120p.e.$$

$$Q_{cb} \leq 0.4$$

$$Q_{cb} \leq 0.5 - \frac{Q_{tot}}{300p.e.}$$

Here, Q_{cb} represents the distribution of deposited charge over the PMTs. A value of $Q_{cb} = 1$ indicates that all the charge is concentrated in one PMT, while $Q_{cb} = 0$ implies that the charge is evenly distributed across all PMTs.

For the preliminary analysis, I have already developed analysis technique to determine the beam correlated neutron background for the full tank volume using ToolAnalysis and ToolDAQ, applying the above neutron selection criteria to a small data sample from the April 2021 Run 2620. The neutron rates for beam spills were determined to be 0.1857 neutrons for CIT backgrounds and 0.0012 neutrons for BI backgrounds. These results fall within the expected range based on the ANNIE's previous results [18].

The next important step is to define the fiducial volume for the neutron multiplicity measurements. To achieve this, we need to evaluate neutron capture efficiency and purity for event selection cuts, optimization of neutron selection cuts, and the assessment of contamination from other particles within the neutron selection criteria.

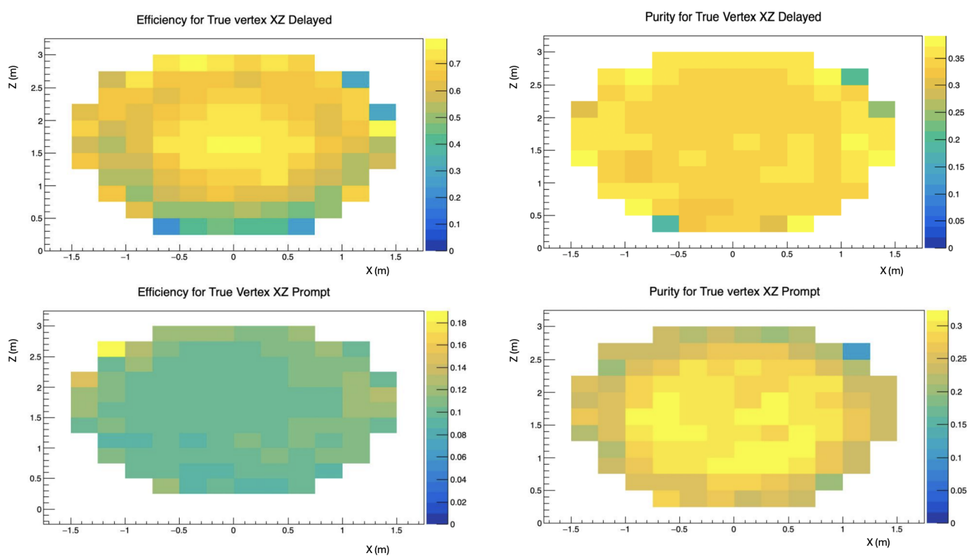

Figure 2.1: Overview of selection efficiency and purity mapped to the Cartesian coordinates of the tank for both the delayed and prompt windows.

2.1.1 *Neutron Selection Efficiency and Purity*

To define FV of the detector, one of the key steps is to calculate efficiency and purity for the events. Using the current neutron selection cuts, I developed a analysis technique to evaluate efficiency and purity based on the Cartesian coordinates of the detector. This tool identifies which areas of the detector exhibit better purity and efficiency in the selection cuts, aiding in the defining of the optimal FV. However, the results show that the current neutron selection cuts have low purity and efficiency across the detector, with the best purity at around 35% and efficiency at approximately 70% in the delayed window. In the prompt window, the purity is around 30%, and the efficiency is barely 20%. The following formulas were used to determine efficiency and purity:

$$\text{Efficiency} = \frac{\text{Selected True Neutrons}}{\text{Total True Neutrons}} \tag{2.1}$$

$$\text{Purity} = \frac{\text{Selected True Neutrons}}{\text{All Selected Clusters}} \tag{2.2}$$

2.1.2 *Neutron contamination*

To identify the primary factors leading to the low purity and efficiency of the current neutron selection cuts, I analyzed the sources of contamination contributing to these issues. Specifically, I calculated the ratio of contaminated particles within the neutron selection cuts compared to all clusters in the WCSim simulation data. The analysis revealed that the majority of contamination arises from gammas, muons, and pions, with each of the other particle types contributing less than 1% to the contamination.

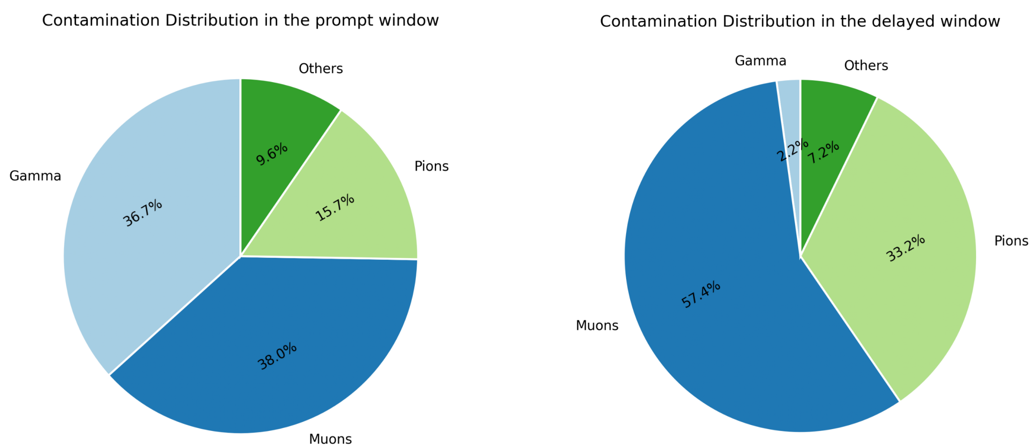

Figure 2.2: Overview of contamination from Muons (μ^- and μ^+), Pions (π^+, π^-, and π^0), Gammas (γ), and other particles in prompt and delayed neutron selections.

2.1.3 *Neutron Selection cuts*

In section 2.1.1, one of the reasons for having low purity and efficiency could be the current neutron selection cuts themselves. To address this, I developed another tool to optimize the neutron selection cuts. This tool calculates efficiency and purity for various possible neutron selection cuts. While it has not provided a solid conclusion yet, it has helped identify that there is potential for better selection and efficiency with a $Q_{cb} \geq 0.45$ and deposited charge $Q_{tot} = [70, 170]$ p.e. Additionally, there may be other issues to address, such as the accuracy of the deposited charge calculation on the PMTs, which could be influenced by limitations in the current simulation. I have contributed to improving the PMT simulation, as described in 2.1.4

2.1.4 *Single PE PMT Waveforms*

Given the presence of various types of PMTs, it is important to ensure that the MC simulations closely replicate the observed data. To achieve this, I contributed to the development of a PMT waveform simulation for modeling the charge deposited on each PMT. Specifically, I determined the fitting parameters for the waveforms of all PMTs. Additionally, I developed the foundational code to implement these fitting parameters on a PMT-by-PMT basis, utilizing a log-normal fit function along with other features by following the PMT waveform reconstruction methods employed in the Daya Bay experiment [19].

2.2 Characterization and Deployment of LAPPDs

For the efforts of Research and Development (R&D) in ANNIE, I visited Fermilab during the summer of 2024, where I participated in characterizing and deploying multiple LAPPDs inside the tank. I have briefly outlined the importance of LAPPDs in 1.2.1. Figure 2.3 illustrates the schematics of LAPPD housing, providing a clear representation of the detector development efforts.

I contributed to evaluating electronic components, including trigger card channels to minimize electronic noise, ACDC (control) cards for signal digitization, LVHV (voltage distribution) boards for the LAPPD electronics. Additionally, I assisted in assembling all the electronics, as shown in Figure 2.3, into waterproof housing and thoroughly tested the setup before deploying individual LAPPDs inside the tank multiple times.

Building on these experiences, I further contributed to preparing and deploying LAPPD 151. This involved assessing all electronic components, creating individual testing setups, and assembling the electronics for LAPPD 151 for characterization in force trigger mode. In this mode, we manually sent signals into a single strip of the LAPPD to evaluate its response to single photons. I conducted a thorough analysis of single photon hits in force trigger mode to determine the threshold value for LAPPD 151, as depicted in Figure 2.4.

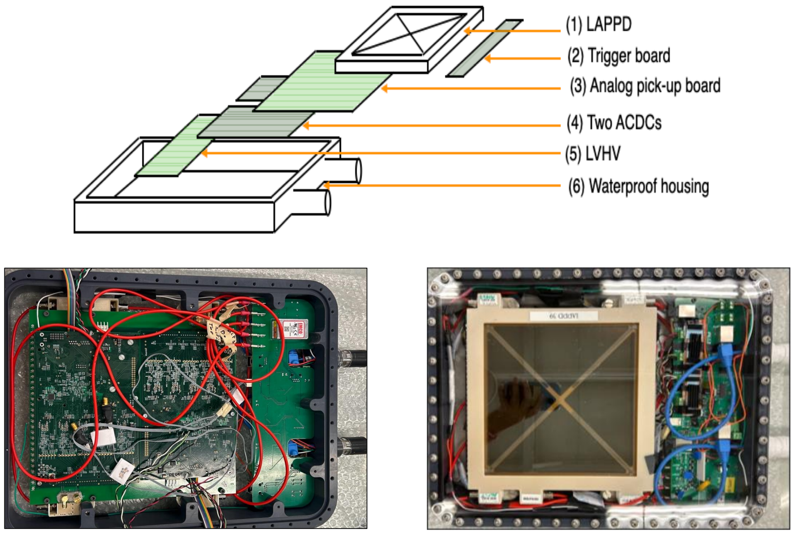

Figure 2.3: Top: Illustration of the LAPPD housing (adapted from [20]). **Bottom:** Assembly of LAPPD 39 with its electronics in the LAPPD housing.

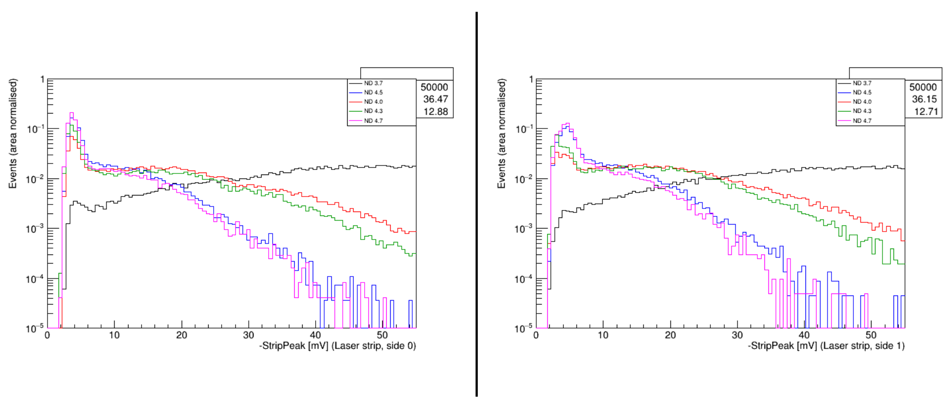

Figure 2.4: Threshold voltage for various Neutral Density (ND) filters to determine the single-photon response of LAPPD 151, with the single-photon peak shown for ND 4.7.

Chapter 3

NEUTRON MULTIPLICITY

3.1 State of art in research

Several experiments, such as MINERvA [6], NOvA [8], Super-K [21], and T2K [9] have made efforts to measure the final-state neutron multiplicity for the neutrino interactions within their experimental environments. However, these experiments observe a lower neutron yield than predicted by their simulations. These challenges arise from limitations in modeling both neutrino interactions (ie. GENIE) and the subsequent interaction of final state particles (ie. WCSim) and the precision of hardware in accurately determining the location of neutrons.

The MINERvA experiment has measured neutron multiplicity from neutrino interactions using 3 GeV and 6 GeV proton beams. As shown in Figure 3.1, the experiment overestimated neutron candidates by 15%, primarily due to the overproduction of neutrons in neutrino interaction simulation. Additionally, the simulation model predicted that 25% of neutrons had kinetic energies below 10 MeV, contributing to a discrepancy between the observed data and the simulated neutron yield at both instances [6, 7].

In the ANNIE experiment, two previous PhD theses have shown preliminary distributions of the neutron multiplicity for neutrino interactions [22, 10]. A significant discrepancy is observed between data and simulation. These analyses did not incorporate contributions from the LAPPDs and neutron vertex reconstruction for determining neutron yields. Additionally, it excluded considerations for fiducial volume accounting for neutron vertex reconstruction and the upgraded AmBe calibrations for optimizing neutron selection cuts. Furthermore, their work did not incorporate all possible systematic uncertainties. These factors present significant opportunities for improving the results by incorporating them into the analysis.

3.2 Neutron multiplicity measurements with PMTs + LAPPDs

The goal of this research is to perform neutron multiplicity measurements for neutrino interactions using PMTs and LAPPDs, which has not done before. This approach of incorporating LAPPDs alongside PMTs significantly improves muon vertex reconstruction, enhancing the resolution of position and timing for neutrino interaction events. ANNIE is capable of detecting neutrino

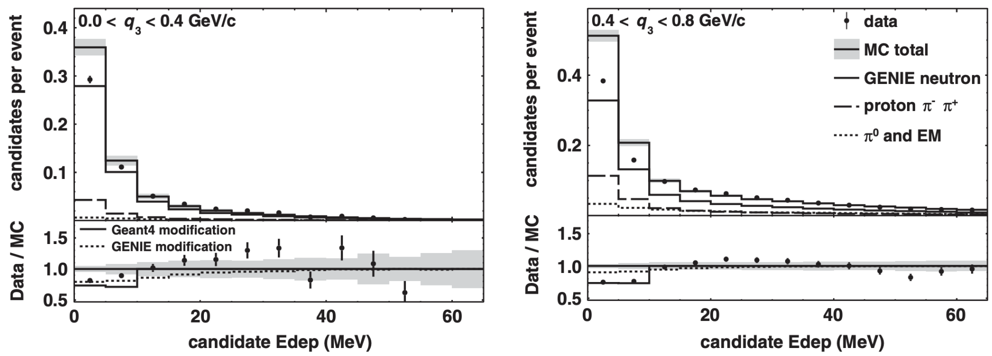

Figure 3.1: Distribution of energy deposition per neutron candidate, including statistical uncertainty in the data and systematic uncertainties in the simulations, for a 3 GeV proton beam at MINERvA [6].

interaction events in the LAPPD subsystem. I plan to develop analysis techniques to integrate LAPPD data into the mainstream analysis, combining it with data from the tank PMTs and MRD subsystem. The analysis will also incorporate the updated AmBe calibration campaign to improve neutron selection cuts. To accurately determine neutron yield for signal events, an extensive study of relevant backgrounds is ongoing, as discussed in 2.1. This will be the first study of background candidates relevant to the neutron-multiplicity analysis in ANNIE. Additionally, current efforts focus on addressing specific issues related to reconstruction of neutron vertex and other low energy events for future ANNIE analyses. The ability to define a fiducial volume for low energy events can also be extended for cross-section analysis in ANNIE, providing broader applications for the experiment's objectives.

In the progression of this PhD research, I will lead the AmBe calibration efforts in ANNIE to ensure the detector response to the neutrons. This involves determining AmBe neutron related background sources along with accounting for systematic uncertainties in the AmBe campaign. The AmBe calibration for better neutron signal definition and collection of high-quality data using LAPPDs and the tank PMTs, along with the integration of this data into developed analysis techniques, will enable me to perform the first measurement of neutron multiplicity from neutrino interactions with better muon vertex and time resolutions.

The unique ability of ANNIE to provide known emitted neutrino energy and advanced instrumentation, which reduces systematic uncertainties in signal studies, will be utilized to perform precise neutron yield measurements. Leveraging these advantages, the analysis aims to contribute to improving neutrino generator simulations, particularly for Final State Interaction (FSI) modeling at low-scale neutron kinetic energies. These improvements will enhance the performance of simulation models in future long-term experiments.

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