NEUTRINO HUNTING: LOOKING THROUGH A UV LENS

SCINTILLATION PHOTON DETECTION IN A LARGE-VOLUME LIQUID ARGON TIME PROJECTION CHAMBER, EXPOSED TO A MULTI-GEV CHARGED PARTICLE BEAM

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The Deep Underground Neutrino Experiment (DUNE) will be a world-class neutrino observatory and nucleon decay detector designed to answer fundamental questions about elementary particles and their role in the universe. The DUNE experiment will consist of a Near Detector, located at Fermilab, and a Far Detector, approximately 1.5 km underground at the Sanford Underground Research Facility in South Dakota, located ∼1300 km away. The accelerator complex at Fermilab will host an intense beam of neutrinos directed toward the two detectors. My dissertation centers on the implementation of technologies used to detect scintillation photon signals in liquid argon in the context of the DUNE’s Far Detector Single-Phase (SP) module design, and features direct contributions to the Photon Detection System (PDS) deployed in the ProtoDUNE-SP Large-Volume Liquid Argon Time Projection Chamber (LArTPC) prototype. The PDS is needed for non-beam event timing, such as atmospheric neutrinos, proton decay, and supernova detection. The PDS provides a prompt signal ($t_0$ information) for micro-second event time determination, which improves the TPC’s spatial localization along drift direction, enables accurate ionization-signal-attenuation determination, and even provides calorimetry.

My dissertation will discuss an overview of the DUNE and ProtoDUNE-SP experiment and how we detect neutrinos in LAr, via charge and scintillation light. It will discuss my core experimental and analysis work, in regards to the Photon Detection System; including my contributions in establishing procedures for the commissioning and integration for the Photon Detector System that will be valuable during the construction, installation, commissioning, and operations of the DUNE Far Detector. In addition, it will comprehensively discuss the capability of three different photon detection technologies, and their characteristics and responses to muon and electron beam
particles over a range of beam momenta, from 0.3 GeV/c - 7 GeV/c. Further, the overall progress detailed in this thesis will help pave the way toward understanding the physical properties of these detectors, which will contribute to the success of the sensitivity measurements required for determining the neutrino mass hierarchy and $\delta_{CP}$. 
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Chapter 1

Introduction and Scientific Background

Neutrinos are everywhere, passing through our bodies at a rate of \( \sim 100 \text{ trillion times/second} \). They are the lightest and most abundant matter particle in the universe, yet they are one of the most challenging particles to detect. Neutrino oscillations could even hold the answers to why we are here (i.e. CP-Violation). Needless to say, neutrinos are fascinating.

Understanding neutrino oscillations has become one of the main science goals in the particle physics community. In the last few decades, enormous efforts have been made to construct large-scale neutrino detectors, in order to detect and understand this elusive particle and its properties. The Deep Underground Neutrino Experiment (DUNE) will be a world-class neutrino observatory and nucleon decay detector, designed to answer fundamental questions about elementary particles and their role in the universe. With its large-scale exposure to neutrino interactions and measurement precision, DUNE aims to refine neutrino oscillation parameters, in particular the mass splitting \( \Delta m^2_{31} \), CP-Violating phase \( \delta_{CP} \), and the mixing angle \( \theta_{23} \), which is vital in determining the neutrino mass ordering and measuring CP-Violation.

The ProtoDUNE-SP experiment represents the largest monolithic Single-Phase LArTPC detector built to date. The detector elements, the Time Projection Chamber (TPC), the cold electronics (CEs), and the Photon Detection System (PDS), are immersed in a cryostat filled with the LAr target material. The TPC is needed for event reconstruction and is used to measure cross sections of interactions of charged particles in LAr. The PDS is needed for non-beam event timing, such as atmospheric neutrinos, proton decay, and SN detection. The PDS provides prompt signal \( (t_0 \text{ information}) \) for micro-second event time determination, which improves the TPC’s spatial localization along drift direction, enables accurate ionization-signal-attenuation determination, and even provides calorimetry.
This dissertation centers on the operation of ProtoDUNE-SP, and the implementation of technologies used to detect scintillation photon signals in the context of the DUNE’s Far Detector Single-Phase (SP) module design. It features my direct contributions to the PDS deployed in ProtoDUNE-SP, including building, commissioning, and operations. Further, it comprehensively reports on the development, light yield, and energy resolution response of three different photon detection technologies at ProtoDUNE-SP.

The outline is as follows: (1) the historical and background physics of neutrinos and what we know today; (2) an overview of the DUNE experiment and its scientific goals; (3) Detecting neutrinos using liquid argon, including the scintillation production and detection; (4) my contributions toward photon detection technology development; (5) an overview of the ProtoDUNE-SP experiment and its experimental goals; (6) my contributions to the production, installation, commissioning, and operations for the Photon Detection System for ProtoDUNE-SP; (7) ProtoDUNE-SP’s analysis and results; (8) conclusion and outlook.

1.1 The Neutrino

Neutrinos are the lightest and most abundant matter particle in the universe and they play an extraordinary role in physics. One of the biggest open questions in physics is the observed imbalance between the abundance of matter and antimatter in the universe. By studying neutrinos, we can probe directly at the asymmetry between matter and antimatter, which in turn can help us try and answer the fundamental question of why we exist. Neutrinos are everywhere, with approximately 100 trillion of them passing through a human’s body every second. There are several natural sources of neutrinos, such as stars, supernovae, the atmosphere, and radioactive decays. However, the main neutrino source comes from relic neutrinos originating from the big bang, with a density of $330/cm^3$ everywhere. Neutrinos can also be produced in large quantities by nuclear reactors or accelerators, delivering intense neutrino beams.
1.2 The Standard Model

Figure 1.1: This figure shows the current standard model of particle physics, describing all known elementary particles. These are grouped by generation (or "families") and are further divided into quarks, leptons and gauge bosons [1].

The Standard Model (SM) of particle physics describes all known elementary particles and their interactions through the fundamental strong, electromagnetic, and weak force (omitting gravity). The electromagnetic force is carried by photons and involves the interaction of electric and magnetic fields. The strong force is carried by gluons, binding together atomic nuclei to make them stable. The weak force, carried by W and Z bosons, governs interactions between hadrons and leptons (as in the emission and absorption of neutrinos) [2].

The SM describes two fundamental particle groups: fermions and bosons. Fermions are elementary particles with spin 1/2 and are made up of quarks and leptons, which are then divided into three generations — shown in the first three columns of Figure 1.1 — each generation increasing in mass compared to the corresponding (column) generation before. Bosons are elementary particles with integer spins and are made up of gauge and scalar bosons, shown in the last two columns of
Despite the apparent completeness of the SM, there are still many unsolved mysteries. We have shown the mechanism that gives particles their mass (Higgs), but we still do not understand what causes the range of masses among the elementary particles. In its current state, the SM could be missing item(s), since we know it still cannot explain the matter-antimatter asymmetry in the universe, nor does it cover the fourth fundamental force: gravity. It also fails to include dark matter, dark energy, as well as the non-zero masses of the neutrinos that are confirmed by the neutrino oscillation phenomenon [3, 2].

1.3 Neutrino History

In 1914, James Chadwick measured the electron spectrum in $\beta$-decay to be continuous instead of a discrete energy spectrum, as expected in a two-body decay. In 1927, Charles Ellis and William Wooster gave direct proof that the electron spectrum was in fact continuous and not discrete [5, 6]. It was not until 1930 that Wolfgang Pauli found a solution to this “possible violation of a fundamental law of physics” problem, proposing that another undetected particle carried away the missing energy. A particle that had to be very light or even massless, and should be a neutral weakly interacting fermion, at the time named the neutron [4].

By 1932 Chadwick had discovered the neutron, which led to Enrico Fermi (in 1934) to rename this neutral weakly interacting particle Pauli proposed the “neutrino”—Italian for “little neutral one”. Fermi proposed a theory that included Pauli’s hypothesized particle, which became the first theory of one of the four fundamental forces, the weak force. Today the fundamental $\beta$-decay process is

$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$ (1.1)

In 1956, Frederick Reines and Clyde Cowan were the first to observe evidence of electron
antineutrinos. The experiment detected inverse \( \beta \)-decay in water containing dissolved cadmium chloride, as part of Project Poltergeist, located at Los Alamos National Laboratory. Still to this day, the neutrino is considered a ghostly particle, going through matter without leaving much of a trace. Since this discovery, multiple neutrino flavors have been discovered: the electron neutrino (\( \nu_e \)), muon neutrino (\( \nu_\mu \)) and tau neutrino (\( \nu_\tau \)), which are so-called weak eigenstates of the neutrino.

In 1968, a chemist at Brookhaven National Laboratory, Ray Davis, led the first experiment to detect electron neutrinos produced by the sun, called solar neutrinos. The experiment used dry cleaning fluid (perchloroethylene) in a huge tank deep underground, in the Homestake Gold Mine in South Dakota, to count neutrinos. However, the experiment found only one-third the number of solar neutrinos predicted by astrophysicist John Bahcall, leading to the solar neutrino problem \[5\].

During this time in 1968, Bruno Pontecorvo proposed that the solar electron neutrinos transformed in flight to other neutrino species like the muon neutrino, which could explain the results made by Davis’ experiment. The Homestake experiment was insensitive to these species and therefore could have missed those neutrinos. Today, this is known as neutrino oscillation, a theory developed in 1975 by Samoil Bilenky and Bruno Pontecorvo \[6\] and was confirmed in 2002 by the Sudbury Neutrino Observatory (SNO) \[7\] that the solar neutrino flux contains a non-electron flavor, suggesting that a fraction of the electron neutrinos changed flavor while travelling between the Sun and the Earth. Thus, neutrinos have non-zero mass, as implied by the oscillation theory.

1.4 Neutrino Oscillation

Neutrinos (and antineutrinos) come in three flavors and exist as doublet charged leptons: (\( \nu_e \), \( e \)), (\( \nu_\mu \), \( \mu \)) and (\( \nu_\tau \), \( \tau \)), each neutrino flavor being a superposition of all three neutrino mass eigenstates: \( \nu_1 \), \( \nu_2 \), \( \nu_3 \). Neutrinos have very small (unmeasured) masses and are the most abundant elementary matter-particles in the universe. Neutrinos have no electrical or flavor charge and only interact with two fundamental forces: the weak interaction coupling to the W and Z bosons, and
gravity. In order to produce a detectable signal, neutrinos must exchange either a W or Z boson with particles in matter, which can then be observed via the (stronger) electromagnetic interactions. Due to their electric nature, neutrino interactions via the Z bosons and the W bosons are called neutral current interactions and charged current interactions, respectively. Common interactions between neutrinos and ordinary matter are shown as Feynman diagrams in Figure 1.2.

Figure 1.2: This figure shows two Feynman diagrams, displaying the main interactions of neutrinos with ordinary matter. Left: how neutral current interactions can involve quarks & electrons. Right: how charge current interactions exchange with quarks.

1.4.1 Neutrino Mixing

As mentioned above, neutrinos come in three flavor states $|\nu_\alpha\rangle$, each flavor being a superposition of three neutrino mass eigenstates: $\nu_1, \nu_2, \nu_3$. Neutrino oscillation is the phenomenon of a neutrino being able to change flavor over time, as it traverses space. Transforming between the flavor and mass states is done with the neutrino mixing matrix:

$$|\nu_i\rangle = U |\nu_\alpha\rangle, \quad |\nu_\alpha\rangle = U^\dagger |\nu_i\rangle$$  \hspace{1cm} (1.2)
where the U refers to the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix and $U^\dagger$ refers to Hermitian conjugation. In the three-neutrino model, the neutrino flavor $\alpha$ can be any of $e$, $\mu$, or $\tau$ while the index $i$ refers to the mass eigenstates 1, 2 and 3. In order to preserve the probability amplitudes between basis transformations, regardless of which basis you start from, the mixing matrix is unitary, i.e., $UU^\dagger = U^\dagger U = I$, and defined as:

$$U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\
    -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\
    s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23}
\end{pmatrix} \begin{pmatrix}
    e^{i\phi_1} & 0 & 0 \\
    0 & e^{i\phi_1} & 0 \\
    0 & 0 & 1
\end{pmatrix}$$

(1.3)

$s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$

such that $\theta_{ij}$ are the three mixing (rotation) angles, $\delta_{CP}$ is the CP-Violation phase, and $\phi_1$ & $\phi_2$ are the Majorana phases. The phases $\phi_1$ and $\phi_2$ are nonzero only if neutrinos are Majorana particles. Majorana phases cannot be investigated in neutrino oscillations and are still under investigation. Thus, we can simplify the mixing matrix to:

$$U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\
    -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\
    s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23}
\end{pmatrix}$$

(1.4)

1.4.2 Oscillation Probability

Mass eigenstates propagate through space as plane waves, therefore we can describe their propagation, given the energy of the mass eigenstate, $E_i$:

$$|\nu_i(t)\rangle = e^{-iE_it/\hbar} |\nu_i(0)\rangle$$

(1.5)

For detectable neutrinos, the momentum of the neutrino is much greater than the mass of the mass eigenstates. Therefore, we can simplify equation 1.5, using ultra relativistic approximation
and in natural units, to:

\[ |\nu_i(t)\rangle = e^{-i\left(p + \frac{m_i^2}{2}\right)x} |\nu_i(0)\rangle = S |\nu_i(0)\rangle \]  \hspace{1cm} (1.6)

The evolution operator S governs the propagation of neutrino states, and is diagonal in the case of pure neutrino mass eigenstates in vacuum. However, since production and detection depend on flavor and not mass, we should view neutrino propagation in terms of the flavor basis. The oscillation probability is the squared absolute value of the oscillation amplitude, in terms of flavor:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\alpha | \nu_\beta \rangle |\nu_\alpha(t)\rangle \right|^2 \]  \hspace{1cm} (1.7)

This leads to the neutrino oscillation probability in a vacuum to be,

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} Re(U_{ij}^{\alpha\beta}) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} Im(U_{ij}^{\alpha\beta}) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right) \]  \hspace{1cm} (1.8)

If we consider substituting the mixing matrix, shown in equation 1.4 given this oscillation probability (equation 1.8), we can see that general oscillation probability is not so simple. Nevertheless, equation 1.8 tells us that neutrinos must have mass, must have a mass difference, and must travel some path for neutrino oscillations to occur. Having three neutrino mass eigenstates implies two independent \( \Delta m^2 \) differences \( \Delta m^2_{21} \) and \( \Delta m^2_{31} \), following a third \( \Delta m^2 \) difference \( \Delta m^2_{32} = m_3^2 - m_2^2 \).

### 1.5 Neutrino Hunting

There are plentiful of natural neutrino sources—coming from stars, supernovae, the earth’s atmosphere, radioactive decays, cosmogenic (big bang), as well as accelerator sources. Neutrino oscillations have been extensively studied over the last decades. Since 2002, KamLAND has been measuring the disappearance of nuclear reactor electron antineutrinos. The KEK to Kamioka (K2K)
Figure 1.3: This figure shows the two possible spectra for the neutrino mass hierarchy. Where \( \Delta m_{21}^2 \ll \Delta m_{31}^2 \), which indicates neutrino mass eigenstates \( \nu_1 \) and \( \nu_2 \) are close together and that \( \nu_3 \) is further apart. The flavor components of each mass eigenstate is indicated by the colors shown [9].

To SuperKamiokande (Super-K) experiments, and the Main Injector Neutrino Oscillation Search (MINOS) experiment have also thoroughly studied neutrino oscillations. Their contributions helped to eliminate the non-oscillation models and to the confirmation of neutrino oscillations, which led to the 2015 Nobel Prize in physics—awarded to Takaaki Kajita (Super-K) and Arthur McDonald (SNO) for the discovery of neutrino oscillations. Other past, present, and future experiments like DUNE, the IceCube Neutrino Observatory, the NOvA, and T2K experiments, all continue to contribute in improving neutrino oscillation measurements and its parameters [10, 11, 12, 13, 14].

1.5.1 Oscillation Parameters

Recent experiments have shown that \( \Delta m_{31}^2 \) dominates the cause for oscillation at the short-baseline scale and \( \Delta m_{21}^2 \) for the long-baseline scale. Further, \( \Delta m_{21}^2 \ll \Delta m_{31}^2 \), which indicates neutrino mass eigenstates \( \nu_1 \) and \( \nu_2 \) are close together and that \( \nu_3 \) is further apart. That being said, the correct orientation of the mass ordering is still under investigation. Figure 1.3 shows the two possible mass
Figure 1.4: This figure shows the distribution of neutrino sources in energy and distance traveled to the detector, depicting present and future experiments aimed at detecting them [15].

Spectra for the neutrino mass hierarchy, where $\Delta m^2_{31} > 0$ is called the normal mass hierarchy, and $\Delta m^2_{31} < 0$ is called the inverted hierarchy. The flavor components $\nu_e$, $\nu_\mu$, and $\nu_\tau$ of each mass eigenstate is indicated by the colors shown, where each flavor is composed of some fraction of each eigenstate [16]. Table 1.1 summarizes typical values of distance ($L$) and energy ($E$) for different types of neutrino sources, and the corresponding ranges of $\Delta m^2$ for which they are most sensitive to flavor oscillations in vacuum [17]. SBL refers to the short-baseline and LBL to long-baseline.

Leptonic CP-Violation can be measured directly by examining neutrino and antineutrino oscillations in the same experiment. This can be done by measuring both the neutrino and antineutrino beam. The effect of CP-Violation is more pronounced at lower energies, which is in contrast to $\Delta m^2$, discussed later in Section 2.2. In general, neutrino oscillation parameter fits are best made by using observations made by all relevant experiments at once, giving us a global fit. The current best-fit values for the neutrino oscillation parameters are shown in Table 1.2.
Table 1.1: This summarizes typical values of distance (L) and energy (E) for different types of neutrino sources, and the corresponding ranges of $\Delta m^2$ to which they can be most sensitive to flavor oscillations in vacuum [17]. SBL refers to the short-baseline and LBL to long-baseline.

| Experiment | L [m]     | E [MeV] | $|\Delta m^2| [eV^2]$ |
|------------|-----------|---------|------------------------|
| Solar      | $10^{10}$ | 1       | $10^{-10}$             |
| Atmospheric| $10^4 - 10^7$ | $10^2 - 10^5$ | $10^{-1} - 10^4$       |
| Reactor    | $10^2 - 10^3$ SBL | 1 | $10^{-2} - 10^{-3}$ | $10^{-4} - 10^{-5}$ |
|            | $10^4 - 10^5$ LBL |       |                        |
| Accelerator| $10^2$ SBL | $10^3 - 10^4$ | $>0.1$                |
|            | $10^5 - 10^6$ LBL | $10^3 - 10^4$ | $10^{-2} - 10^{-3}$ |

Table 1.2: Best-fit values for the neutrino oscillation parameters by a global fit that makes use of the results of a wide variety of experiments, using the assumptions of the normal hierarchy (N-H) and inverted hierarchy (I-H) [18].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Best fit $\pm 1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N-H</td>
</tr>
<tr>
<td>$\theta_{12}[^\circ]$</td>
<td>Solar oscillation angle</td>
<td>$33.44^{+0.77}_{-0.74}$</td>
</tr>
<tr>
<td>$\theta_{23}[^\circ]$</td>
<td>Atmospheric oscillation angle</td>
<td>$49.2^{+0.9}_{-1.1}$</td>
</tr>
<tr>
<td>$\theta_{13}[^\circ]$</td>
<td>Reactor oscillation angle</td>
<td>$8.57^{+0.12}_{-0.12}$</td>
</tr>
<tr>
<td>$\delta_{CP}[^\circ]$</td>
<td>CP-Violating phase</td>
<td>$197^{+27}_{-24}$</td>
</tr>
<tr>
<td>$\Delta m^2_{21}[10^{-5}eV^2]$</td>
<td>Long range oscillation</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
</tr>
<tr>
<td>$\Delta m^2_{31}[10^{-3}eV^2]$</td>
<td>Short range oscillation</td>
<td>$2.517^{+0.026}_{-0.028}$</td>
</tr>
</tbody>
</table>
Table 1.3: A list of past, present, and future neutrino long-baseline experiments [17]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam Line</th>
<th>Far Detector</th>
<th>L [km]</th>
<th>$E_{\nu}[GeV]$</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>KEK-PS</td>
<td>Water Cerenkov</td>
<td>250</td>
<td>1.3</td>
<td>1999-2004</td>
</tr>
<tr>
<td>MINOS</td>
<td>NuMI</td>
<td>Iron-scintillator</td>
<td>735</td>
<td>3</td>
<td>2005-2013</td>
</tr>
<tr>
<td>MINOS+</td>
<td>NuMI</td>
<td>Iron-scintillator</td>
<td>735</td>
<td>7</td>
<td>2013-2016</td>
</tr>
<tr>
<td>OPERA</td>
<td>CNGS</td>
<td>Emulsion</td>
<td>730</td>
<td>17</td>
<td>2008-2012</td>
</tr>
<tr>
<td>ICARUS</td>
<td>CNGS</td>
<td>Liquid Argon TPC</td>
<td>730</td>
<td>17</td>
<td>2010-2012</td>
</tr>
<tr>
<td>T2K</td>
<td>J-PARC</td>
<td>Water Cerenkov</td>
<td>295</td>
<td>0.6</td>
<td>2010-Present</td>
</tr>
<tr>
<td>NO$\nu$A</td>
<td>NuMI</td>
<td>Liquid scintillator + tracking calorimeter</td>
<td>810</td>
<td>2</td>
<td>2014-Present</td>
</tr>
<tr>
<td>DUNE</td>
<td>LBNF</td>
<td>Liquid Argon TPC</td>
<td>1300</td>
<td>2-3</td>
<td>expected 2030</td>
</tr>
<tr>
<td>HYPER-K</td>
<td>J-PARC</td>
<td>Water Cerenkov</td>
<td>295</td>
<td>0.6</td>
<td>expected 2027</td>
</tr>
</tbody>
</table>

1.5.2 Continuing to Hunt

Moving forward, the next generation neutrino experiments will prioritize measuring $\delta_{CP}$ and determining the neutrino mass hierarchy. Table 1.3 shows a list of past, present, and future neutrino long-baseline experiments. Even with the wealth of neutrino information we have obtained thus far—as shown in Table 1.2—current neutrino experiments remain limited. As such, a collective international effort is ongoing to build new and better detectors. Two main leading-edge long-baseline neutrino oscillation experiments are already underway: the Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (Hyper-K).

The Hyper-K experiment is based on Water Cerenkov technology, located in Japan, and is expected to take its first data in 2027 [19]. DUNE is based on Liquid Argon Time Projection Chamber (LArTPC) technology and is expected to take its first data in 2030 [20]. Both experiments are going to be an order of magnitude larger than their corresponding predecessor, and have a more intense neutrino beam. This will allow a substantial increase in our measurement sensitivity. Further,
these upgrades will aim to measure CP-Violation with a $5\sigma$ significance, as well as determine the correct neutrino mass hierarchy.
Chapter 2

DUNE

The Deep Underground Neutrino Experiment (DUNE) is an upcoming international long-baseline experiment that is expected to start producing physics results by 2030. DUNE’s physics objectives are to search for CP-Violation, the neutrino mass hierarchy, supernova neutrino detection, and searches for nucleon decay. DUNE will consist of two neutrino detectors placed in the world’s most intense neutrino beam. The Near Detector (ND)—located at Fermi National Accelerator Laboratory—will monitor and characterize the beam intensity and energy, and the Far Detector (FD) —located 1.5 km underground at the Sanford Underground Research Facility in Lead, South Dakota—will allow us to measure precise neutrino oscillation parameters. The intense neutrino beam will be produced by Fermilab’s accelerator complex, pointed downstream toward the FD 1300 km away. This long baseline will allow for sensitive neutrino oscillation measurements, required for the determination of the neutrino mass hierarchy and $\delta_{CP}$.

The Near Detector is composed of three ND modules, each employing different technologies, described in Section 2.4. The Far Detector is composed of four independent 10kt (fiducial mass) FD modules, each based on the Liquid Argon Time-Projection Chamber (LArTPC) technology, described in detail in Section 2.5. My thesis centers on the implementation of technologies used to detect scintillation photon signals in LAr in the context of the DUNE Far Detector module design.

This chapter is intended to be an overview of the DUNE experiment and the detector components needed to achieve its physics goals, as well as the relevance toward my thesis. The following sections will describe DUNE’s scientific goals, its measurement capabilities, as well as its Near and Far Detector components. For more specific details, please refer to our DUNE published articles [22, 23, 20, 24, 25, 26, 27].
Figure 2.1: This figure shows a schematic depiction of the DUNE Experiment. Originating at Fermilab, a neutrino beam (produced by a proton beam, capable of delivering 1.2 MW of power) passing through its Near Detector, travelling $\sim 1300$ kilometers through the Earth’s crust to its Far Detector—located 1.5 kilometers underground in Lead, South Dakota [21].

2.1 Scientific Goals of DUNE

DUNE’s main physics objectives are to measure leptonic CP-Violation and determine the neutrino mass hierarchy. The Near and Far Detector aims to measure both low and high energy spectra for neutrinos and antineutrinos simultaneously, in order to obtain all neutrino oscillation parameters at the same time. Determining $\Delta m_{31}^2$ is vital for understanding a nonzero CP-Violating phase $\delta_{CP}$, which would indicate leptonic CP-Violation. With DUNE’s high precision measurements of $\nu_\mu$ and $\nu_e$ oscillations, we can determine the neutrino mass hierarchy with a significance of at least 5$\sigma$ within years of operations. In addition, it will reach 5$\sigma$ sensitivity to CP-Violation for 50% of possible values in $\sim 10$ years [24].

Beyond DUNE’s main physics objectives, it aims to study supernova neutrino bursts, searches for nucleon decay, and carry out dark matter and beyond standard model (BSM) searches [20]. DUNE’s Far Detector is sensitive to near Earth ($< 100$ kpc) supernova neutrino burst (SNB) events. Detecting such events can not only help DUNE, but this detection can also become an
early supernova signal—signaling observatories to orient their telescopes in the same direction to gain more insight (via photon detection) and better understand the physical processes in early stages of a star core-collapse and possibly, black hole formation [20]. In addition, the Far Detector shields against cosmic rays, since it is located 1.5 km underground. Together with its large active detector mass, this shield gives DUNE the opportunity to search for nulceon decay. Grand unification theories (GUTs) that aim to unify the electromagnetic, weak, and strong force at high energies predict that baryon number conservation is not exact, and that protons and bound neutrons are not stable as a result.

2.2 DUNE Measurements

In order for DUNE to reach its physics goals, it needs to record a large volume of neutrino oscillation data over a large period of time. DUNE will start recording data while it is only partially completed, being modular by design, in order to produce the statistics needed. The amount of exposure required for measuring the neutrino mass hierarchy to at least 5σ depends on the final beam design, and other oscillation parameters, namely δCP and the mass hierarchy itself.

2.2.1 Neutrino Mass Hierarchy

DUNE’s neutrino beam and long baseline (through the Earth’s crust) implies a significant impact on oscillation probabilities by matter effects. For accelerator-produced neutrinos traveling through the Earth, the neutrinos are subject to scattering off of electrons in the medium. Different from the other flavors, νe and νe have contributions from charge current (CC) and neutral current (NC) scattering, described more in Section 3.1. This adds a potential to the Hamiltonian describing the oscillations, as \( V(x) = \sqrt{2G_FN_e(x)} \), with \( G_F \) being the Fermi constant and \( N_e(x) \) being the electron density [28]. The origin of this matter effect is due to the Mikheyev-Smirnov-Wolfenstein effect (MSW) [29], which influences electron neutrinos in the few-GeV energy range. More precisely,
a resonance occurs for $\nu_e$ in the case of a normal hierarchy, and for $\bar{\nu}_e$ in the case of an inverted hierarchy [24]. The asymmetry from this matter effect increases with baseline distance ($L$), as neutrinos pass through more matter. Therefore an experiment with a longer baseline, such as DUNE’s (1300 km), will be sensitive to neutrino mass hierarchy measurements, and will be able to resolve the degeneracy between the asymmetries from matter and CP-Violation effects—unambiguously determining the neutrino mass hierarchy and $\delta_{CP}$.

Figure 2.2 shows the appearance probability, $P(\nu_\mu \to \nu_e)$, of DUNE’s 1300 km baseline, as a function of neutrino energy for several values of $\delta_{CP}$. This figure illustrates the value of $\delta_{CP}$ affecting both the amplitude and phase of the oscillation. The probability amplitude increases in difference between the values of $\delta_{CP}$ at higher oscillation nodes, which corresponds to energies less than 1.5 GeV. Therefore it is important that a broadband experiment, such as DUNE, has the capability of measuring not only the rate of $\nu_e$ appearance, but also the oscillation spectrum down to energies of at least 500 MeV [24]. Figure 2.3 further illustrates the influence $\delta_{CP}$ and the mass ordering itself has on the mass hierarchy measurement.

### 2.2.2 CP-Violation

As alluded to in Section 1.5.1, leptonic CP-Violation can be measured directly by examining neutrino and antineutrino oscillations in the same experiment. DUNE can measure this neutrino asymmetry by the normalized difference between neutrino and antineutrino appearance:

$$A_{\mu e} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \quad (2.1)$$

Figure 2.4 shows that the behaviour of $A_{\mu e}$ is quite different for the two most important oscillation nodes in the neutrino energy spectrum, shown by vertical lines. Around the first oscillation maximum at 2.5 GeV, the asymmetry flips sign between mass hierarchies, but is relatively unchanged by $\delta_{CP}$. Around the second oscillation maximum of 0.9 GeV, however, the asymmetry remains nearly unchanged between mass hierarchies, but varies drastically for different values of $\delta_{CP}$. Figure 2.5
Figure 2.2: This figure shows the appearance probability at a baseline of 1300 km, as a function of neutrino energy, for $\delta_{CP} = \pi/2$ (blue), 0 (red), and $\pi/2$ (green), for neutrinos (left) and antineutrinos (right), for normal hierarchy. The black line indicates the oscillation probability if $\theta_{13}$ were equal to zero [24].

Further details these effects. The first oscillation maximum at 2.5 GeV (right) shows insight to the value of $\delta_{CP}$, regardless of the mass hierarchy. The second oscillation maximum at 0.9 GeV (left) shows insight to the mass hierarchy, regardless of the value of $\delta_{CP}$.

The ability to determine CP-Violation ( $\delta_{CP} \neq 0, \pm \pi$) is dependent on $\delta_{CP}$’s true value [24]. Figure 2.6 illustrates the sensitivity to CP-Violation, as a function of CP-Violating phases. As indicated, if the true value is closer to 0 or $\pm \pi$, it could take decades to reach the 5$\sigma$ level, even with DUNE’s high precision measurements.

The significance of the mass ordering and CP-Violation measurements, as a function of time, is shown in Figure 2.7. The small ridges (kinks) indicate the enhancements and additional detector module contributions anticipated by DUNE [24]. As expected (from Figure 2.3 and 2.6), the mass ordering measurement is anticipated to be well understood long before $\delta_{CP}$. 
Figure 2.3: This figure illustrates the influence $\delta_{CP}$ and the mass ordering itself have on the mass ordering measurement [24].

### 2.2.3 Other Oscillation Parameters

DUNE also aims to increase the resolution of other oscillation parameters, such as the mixing angle $\theta_{23}$. Current measurements of $\sin^2 \theta_{23}$ leave an ambiguity as to whether the value of $\theta_{23}$ is in the lower octant (less than 45°), the upper octant (greater than 45°), or exactly 45°. A global analysis of oscillation measurements (NuFIT 4.0 [31, 24]) has found the value of $\sin^2 \theta_{23}$ to be in the upper octant. However the distribution of their $\chi^2$ has another local minimum in the lower octant. Therefore, the octant is still largely undetermined, as a maximal mixing value of $\sin^2 \theta_{23} = 0.5$ is still allowed. If $\theta_{23}$ were to exactly equal to 45°, this would indicate that $\nu_\mu$ and $\nu_\tau$ have equal contributions from mass eigenstate $\nu_3$, which could be evidence for a previously unknown symmetry. Further, values of $\theta_{23}$ in the lower octant lead to the best sensitivity to CP-Violation and the worst sensitivity to the neutrino mass hierarchy, while the reverse is true for the upper octant. It is therefore important to experimentally determine the value of $\sin^2 \theta_{23}$ with sufficient precision to determine the octant of $\theta_{23}$. The high statistics of DUNE should allow us to achieve this.
Figure 2.4: This figure shows the neutrino appearance asymmetry $A_{\mu e}$, as a function of the neutrino energy for various values of $\delta_{CP}$. Both the normal (left) and inverted (right) mass hierarchy are shown. The first and second oscillation maximums are indicated with vertical lines around 2.5 and 0.9 GeV, respectively [30].

2.3 Neutrino Beam

The intense neutrino beam will be produced by Fermilab’s accelerator complex, generated from a proton beam, capable of delivering 1.2 MW of power to the neutrino production target. As neutrinos cannot be directed or accelerated, due to its electrically neutral nature, the neutrino beam is obtained by secondary particles that can be manipulated. This is accomplished by accelerating protons to energies 60-120 GeV, and then directing them onto a graphite target. These energetic collisions produce charged pions and kaons, which are focused using magnetic horns. The horns lead these secondary particles through a long 194 m stretch of decay pipe that is filled with helium. During this journey, these secondary particles decay into neutrinos and charged by-products. This produced neutrino beam is angled at $\sim 5.79^\circ$ downward from the horizontal (into the Earth), which allows the beam to remain within the Earth’s curvature and aim directly at the Far Detector, located in Lead, South Dakota.

It will be possible to control the direction of the current flow in the magnetic horns, leading to focusing of either positive or negative charged secondaries, and therefore, it will be possible to
Figure 2.5: This figure shows the neutrino appearance asymmetry $A_{\mu e}$, as a function of $\delta_{CP}$ and the two mass hierarchy possibilities, shown both for a neutrino energy of 0.9 GeV (left) and 2.5 GeV (right) [30].

create a neutrino or antineutrino beam [20]. The beam characteristics are vital for DUNE’s research goals. Table 2.1 shows a summary of the LBNF proton beam design parameters [27].

Table 2.1: This table shows a summary of the LBNF proton beam design parameters for DUNE [27].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Potential upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>60GeV</td>
<td>120GeV</td>
</tr>
<tr>
<td>Protons per cycle</td>
<td>$7.5 \times 10^{13}$</td>
<td>$7.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Spill duration [s]</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Cycle time [s]</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>POT per year</td>
<td>$1.9 \times 10^{21}$</td>
<td>$1.1 \times 10^{21}$</td>
</tr>
<tr>
<td>Beam power [MW]</td>
<td>1.03</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Neutrino flux distributions are determined by the proton beam, the focusing of the magnetic horns, and the target and its location relative to the horns. As described above, depending on its energy, every proton on target (POT) produces a certain number of charged mesons, resulting in neutrino production. For every POT, the Near Detector can expect an average flux of $1.14 \times 10^{-3} \, \nu/m^2$ and the Far Detector can expect $1.65 \times 10^{-10} \, \nu/m^2$. In neutrino mode, the
Figure 2.6: This figure illustrates the sensitivity to CP-Violation, as a function of CP-Violating phase [24].

beam will consist mostly of \( \nu_\mu \) neutrinos, with minor contamination from \( \nu_e \) (\( \sim 0.5\% \)) and various antineutrinos (\( \sim 5\% \)), as shown in Figure 2.8 [32].

2.4 Near Detector

The Near Detector’s main role is to serve as the experiment’s control. It will give us a high-statistics characterization of the neutrino beam close to the source—measuring the unoscillated neutrino interaction rate—which will be extremely useful for tuning the neutrino interaction model used to move between the beam model and the observed data. The ND will also have the capability of taking data at different off-axis beam positions, providing data sets of different beam spectra, and will allow us to deconvolve the beam and cross section models.

To reach to the precision needed for DUNE, the experiment must maximize resolution and minimize systematic uncertainties. Therefore, the ND must have multiple independent methods for measuring neutrino fluxes and significantly outperform the FD. The conceptual design of the ND is based on the collective experience of many current generation neutrino experiments, such as MI-
Figure 2.7: This figure shows the significance of the mass ordering and CP-Violation measurements, as a function of time. The small ridges (kinks) indicate the enhancements and additional detector module contributions anticipated by DUNE [24].

NOS, MiniBooNE, T2K, NOvA, MINERvA, and the Short-Baseline Neutrino [SBN] program [22].

As mentioned, DUNE’s Near Detector will be located approximately 574m from the neutrino beam and has three primary detector components: (1) a highly modular LArTPC, based on ArgonCube technology, called ND-LAr (2) a magnetized gaseous argon TPC, called ND-GAr (3) a magnetized beam monitor, called the System for on-Axis Neutrino Detection (SAND); with ND-LAr and ND-GAr being able to move and take data in positions off the beam axis.

2.4.1 ND-LAr

In order to reduce the cross section and detector systematic uncertainties for oscillation analyses, the first module needs to have the same active material as the FD for an accurate comparison. Therefore, the ArgonCube technology is used as the first of three primary detectors for the ND. The ArgonCube technology utilizes detector modularization to improve drift field stability, allowing for a reduction in high voltage (HV) and LAr purity requirements. In addition, the ArgonCube has a pixelized charge readout which provides unambiguous 3D imaging of particle interactions and
Figure 2.8: DUNE’s neutrino flux expected at Near Detector, in neutrino mode. These simulations were performed with the G4LBNF framework, using current predicted oscillation parameters [32]. The beam will consist mostly of $\nu_\mu$ neutrinos, with minor contamination from $\nu_e$ ($\sim 0.5\%$) and various antineutrinos ($\sim 5\%$) [30].

...can dramatically simplify the reconstruction of neutrino interaction events [33]. It also contains a scintillation photon detection module, called ArCLight[34], which can be placed inside the field cage (FC) to increase light yield and improve the localization of photon signals.

2.4.2 ND-GAr

Downstream of the ND-LAr detector is the magnetized gaseous argon component, ND-GAr, which serves as a muon spectrometer for the ND-LAr detector. The ND-GAr detector uses a pressurized gaseous argon TPC which is surrounded by an electromagnetic calorimeter (ECAL) that is engulfed in a magnetic field generated by a superconducting solenoid. The TPC design is based on the ALICE detector [35]. The excellent space-point resolution of ND-GAr enables precise determination of the efficiency of the Near and Far LArTPC Detectors [36]. The gas detector will play a key role in
Figure 2.9: This figure shows a schematic depiction of DUNE’s ND hall and its three primary detectors, all in the *on-axis* configuration (left) and with the ND-LAr and ND-GAr in the *off-axis* configuration (right). The SAND detector is shown in position on the beam axis. Note the beam axis & direction is shown [22].

determining to the extent to which the FD and ND LAr performance lead to event reconstruction error, mainly since pions have a much lower probability of being misidentified as protons in high pressure gaseous argon than in LAr detectors.

### 2.4.3 SAND

The third primary detector is the System for on-Axis Neutrino Detection (SAND) detector, which acts as a beam monitor. As both the ND-LAr and the ND-GAr detectors can take data at different positions (*on* or *off* axis), it is vital to make sure the beam remains stable, therefore keeping 1/3 detectors stationary. This allows for constant beam monitoring and determination of any distortions to be identified immediately. SAND is largely based on a reuse of the magnet and calorimeter from the KLOE experiment, which was originally intended to probe CP-Violation in neutral kaon decays [37]. For the ND, SAND will consist of a three-dimensional scintillator system, embedded in a gaseous TPC, that is itself embedded in an electromagnetic calorimeter. In addition, it will
be instrumented with a target + tracking system and will have the beam entering perpendicular to the magnetic field. Overall, SAND will improve neutrino energy resolution and reduce the bias in the neutrino energy measurement, leading to a reduction in the relative systematics [27].

2.5 Far Detector

The Far Detector’s role is to serve the experiment’s main physics goals, described in Section 2.1. The expected neutrino flux at the FD, shown in Figure 2.10, will be $\sim 1.65 \times 10^{-10} \, \nu/m^2$, with its main neutrino signals depending on $\nu_e / \bar{\nu}_e$ appearance and $\nu_\mu / \bar{\nu}_\mu$ disappearance probabilities. To meet the physics goals of DUNE, the FD must be able to detect these neutrinos with high efficiency and good energy resolution for a broad energy range. This detector will give us sub-centimeter spatial resolution for charged particle trajectories, enabling neutrino interaction reconstruction and rare event searches; detecting MeV-scale interactions of solar and SNB neutrinos, all the way to the GeV-scale interactions of neutrinos coming from DUNE’s neutrino beam.

DUNE’s Far Detector will be 1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The detector will consist of four individual modules, each filled with a 10 kt fiducial (17 kt actual) mass volume of LAr, with the inner-dimensions being $\sim 15.1 \, m \times 14.0 \, m \times 62 \, m$ and an outer-dimension of $\sim 17.8 \, m \times 18.9 \, m \times 65.8 \, m$, as shown in Figure 2.11. Each module will be identical in dimensions, but with possible different LAr technologies.

2.5.1 FD1-HD

The first FD module planned is called Horizontal-Drift (HD), which is based on LArTPC technology and LAr Photon Detection (LArPD) technology. LArTPC and LArPD technologies will analyze the energy deposited by charged particle-argon interactions, via charge and light. A LArTPC consists of a cathode and an anode. The cathode is biased negative with a high potential, and the anode is set to ground. The result is an electric field that drifts ionized electrons, produced by
Figure 2.10: These plots show the expected FD $\nu$ (left) and $\bar{\nu}$ (right) flux with the beam in *neutrino mode*. These simulations were performed with the GloBES framework, using current predicted oscillation parameters [38]. Note the scale difference between the plots shown, as it is expected that antineutrino contamination will have a lower flux [30].

High-energetic charged particles traversing LAr, toward the anode. The ionized electron signal is detected using a set of induction and collection wire planes that are wrapped around the Anode Plane Assembly (APA). These interactions are described in much detail in Chapter 3.

The Far Detector HD module (FD1-HD) will have a LArTPC, well defined later in Section 3.2.1, composed of alternating anode and cathode plane assemblies, resulting in four *horizontal* 3.6 m drift volumes, each being about 60 m in length. These anode-cathode assemblies are electrically controlled and modularized using a field cage (FC) to maintain and stabilize the electric fields between drift volumes. Within the anode planes will be the photon detector (PD) modules. Figure 2.12 illustrates the LArTPC for FD1-HD, displaying the alternating 58.2 m long (into the page), 12.0 m tall anode and cathode planes, as well as the FC that surrounds the drift regions between the anode and cathode planes[25].
Figure 2.11: This figure shows a schematic depiction of DUNE’s FD cavern, located at SURF in Lead, South Dakota. This detector will consist of four individual modules, each filled with a 10kt fiducial (17kt actual) volume of LAr, with the inner-dimensions being $\sim 15.1 \text{ m} \times 14.0 \text{ m} \times 62 \text{ m}$ and an outer-dimension of $\sim 17.8 \text{ m} \times 18.9 \text{ m} \times 65.8 \text{ m}$ [25].

**Anode Plane Assembly**

The ionized electron signal, produced by high-energetic charged particles traversing LAr, is detected using a set of induction and collection wire planes that are wrapped around the Anode Plane Assembly (APA). Each anode plane is constructed by joining multiple APAs, each 6 m high and 2.3 m wide. An APA consists of a frame that holds four parallel copper wire planes on each of its two faces. The first two planes of wires wrap around to cover both faces of an APA, having a 4.67 mm pitch. The third plane (on both faces) are not electrically connected and have a 4.79 mm pitch. The fourth plane being a wire mesh to evenly terminate the electric field and improve the uniformity of field lines around the wire planes. Signals from the wires of each APA are read out via a total of 2,560 electronics channels.

The wire plane with a $0^\circ$ angle with respect to vertical is called the collection (X) plane. The other two are induction (U,V) planes that are at an angle of $\pm 35.7^\circ$, with respect to vertical.
Figure 2.12: This figure shows a schematic depiction of DUNE’s first 10 kt Horizontal Drift (HD) module, showing the alternating 58.2 m long (into the page), 12.0 m high anode (A) and cathode (C) planes, as well as the field cage (FC) that surrounds the drift regions between the anode and cathode planes [22].

Having the wires of each plane oriented at different angles with respect to those making up the other planes allows for 3D reconstruction [23]. Figure 2.13 shows a schematic of an APA.

**Cathode Plane Assembly**

The cathode plane is meant to carry the necessary HV in order provide the target nominal electric drift field of 500 V/cm. The cathode plane will be an array of 18 Cathode Plane Assemblies (CPA) modules, each 6 m by 3 m, and consisting of flame-retardant (FR4) frames 1.18 m wide and 2 m high. These frames hold thin panels with a resistive coating on both sides to form constant potential surfaces. Figure 2.12 shows two CPA arrays spanning the length and height of a FD1-HD module. To reach the electric drift field of 500 V/cm, for the wide stretch of 3.6 m, the CPA will be held at -180 kV; working with a supporting Field Cage (FC), the CPA will maintain electric...
Photon Detector System

The LArTPC provides excellent particle track resolution for a large LAr detector. However, determining the absolute position of an event interaction is difficult. Fortunately, LAr is an excellent scintillation source, which produces tens of thousands ($\sim 40,000$) of photons per MeV. This prompt scintillation light signal can be detected and a prompt timestamp of an event interaction can be determined—we call this prompt timestamp $t_0$. Relative to the drift charge (electrons), these photons travel almost instantaneously and can help correct the time and spatial localization of such an event interaction. This scintillation light will also contribute to background rejection, calorimetry information, nucleon decay, neutrino reconstruction from supernova bursts, and other cosmological sources. Therefore, creating a Photon Detection System (PDS) is critical for the DUNE physics program.
To meet the challenge of high acceptance for scintillation photon detection, at modest component and fabrication costs, several detector concepts with distinctive features have been independently developed for DUNE. This section will give a brief overview of a general photon detector concept, as the PDS technology for DUNE will be discussed at great length in Chapter 4.

The FD1-HD photon detector (PD) modules view the LAr volume through each face of an APA. Each APA contains 10 support structures behind the wire planes to support these modules. Consequently, these modules are designed as long, thin bars oriented horizontally (\(\hat{z}\) direction) and perpendicular to the \(\hat{x}\) drift direction, each module separated by about 60 cm in the \(\hat{y}\) vertical dimension.

Therefore, the design requirements that must be met by the DUNE FD PDS: (1) the PDS must be sensitive to low levels of light (0.5 photo-electron/MeV of energy deposition); (2) have a minimum timing resolution of 100 ns; (3) it must not interfere with the operation of the TPC and fit within the APA as just described; (4) it must be implemented so as to minimize cost, while maximizing light detection efficiency. Figure 2.14 shows an example (taken from my work on the ProtoDUNE-Single Phase detector) of the three proposed PDS module designs for DUNE (described in detail in Section 5.3), and how they are installed into an APA.

### 2.5.2 FD2-VD

The second FD module planned is called the Vertical Drift (VD) module, shown in Figure 2.15. It is very similar to FD1-HD, since it is also based on LArTPC and LArPD technologies. However, the Far Detector VD module (FD2-VD) has some key differences:

- FD2-VD has a larger drift distance of 6.5 m, instead of 3.6 m
- FD2-VD’s anode plane will be made out of printed circuit boards (PCBs), instead of wire planes
- FD2-VD consists of a TPC where the electrons drift vertically, both upward and downward, instead of horizontally; having 2 LAr volume, as opposed to 4
Figure 2.14: This figure shows an example (taken from my work on ProtoDUNE-Single Phase) of the three proposed PDS module designs for DUNE, and how they are installed into an APA. Each photon detector module is shaped as long, thin bars oriented in parallel to an APA ($\hat{z}$ direction) and perpendicular to the electron drift ($\hat{x}$) direction; behind the wire planes at a distance of $\sim 60$ cm from one another in the $\hat{y}$ vertical dimension.

- FD2-VD will have two different TPC Cold Electronic (CE) readout systems, one of which will have access to interchange readout electronics while running.
- FD2-VD will have a more enhanced Photon Detection System (PDS), with PD modules mounted within the cathode and on cryostat walls, instead of behind the anode plane

CRP

As mentioned, the anode plane will serve a similar function and aim for a similar level or performance to that of FD1-HD, but instead will be constructed out of perforated printed circuit boards
The Vertical Drift TPC concept

The LAr Time Projection Chamber technology:
▶ detectors with large fiducial volumes
▶ high imaging capabilities
→ excellent kinematic reconstruction with a mm-scale spatial resolution.

VD-TPC summarized:
▶ Cathode hanging at mid-height
▶ Bias voltage: -300kV
▶ Field cage ensures Efield uniformity, 500 V/cm
▶ Electrons drift vertically over 6.5m
▶ Anodes: perforated PCB, on the top and bottom of the detector
▶ Photon-sensors on cathode

Figure 2.15: This figure shows a schematic depiction of DUNE’s second 10 kt Vertical Drift (VD) module (FD2-VD), having 4 main differences with the HD detector: (1) it consists of a TPC where the electrons drift vertically, both upward and downward: having 2 LAr volume, as opposed to 4; (2) it has a larger drift distance of 6.5 m; (3) the anode plane will be made out of PCBs instead of wire planes; (4) it will have a more enhanced Photon Detection System (PDS), with placing the PD modules inside the cathode and cryostat walls [39].

(PCBs) instead of wire planes, and is called a Charge Readout Plane (CRP). There are a number of advantages to using a CRP as opposed to an APA, such as manufacturing optimization, reduction in production mistakes and assembly errors due to the simplicity of the multi-layered PCBs, and that the CRP can be accessed for electronic replacement during the detector lifetime.

As in the APA, the CRP has a collection, shield, and two induction planes. The physical structure is also different, with a CRP being 3m by 3.4m. Figure 2.16 shows a schematic and details of the FD2-VD 1/2 CRP. For the electric drift field of FD2-VD, the cathode concept is almost identical to the FD1-HD (ignoring metrology), and the anode (CRP) will be four CRPs
Figure 2.16: This figure shows a schematic and details of a 1/2 Charge Readout Plane (CRP). Though similar to an APA, the CRP is constructed out of printed circuit boards (PCBs), instead of wire planes [39].

In this 3-view design, the 3rd (collection) view strips remain orthogonal to the beam. The 1st view is set along the diagonal of the CRU (45°). Strips across the long gap between a pair of CRUs on the same CRP are interconnected to save readout channels.

- Channel count per CRU pair
- 1st view: 384
- 2nd view: 640
- 3rd view: 576

Figure 2.17: This figure shows a schematic of a FD2-VD Super-structure, composed of four CRP modules. One Super-structure will be the anode side of FD2-VD electric drift field [39].
combined into a large *Super-structure*, shown in Figure 2.17

Since the ionization drift direction in the FD2-VD detector is vertical, it has a *top* CRP, which makes it possible to install the readout electronics inside chimneys, close to the cryostat roof. Therefore, electronic replacement is accessible throughout the detector's lifetime. The CRPs servicing the bottom half of the LAr volume will necessarily be submerged and inaccessible. For both FD1-HD APA and FD2-VD bottom CRP readout, the Cold Electronics (CE) are very similar and will be discussed in Section 3.2.1.

These first two LArTPC modules are projected to be put into operation as part of the DUNE Far Detector by 2027, with two additional modules to be installed by 2030 [25]. The last two FD modules will be LArTPCs, but are still undecided as to which LArTPC technology to use.
Chapter 3

Detecting Neutrinos in LAr

The first direct detection of a neutrino event occurred in 1970 by a 12-foot hydrogen bubble chamber experiment, named the Zero Gradient Synchrotron, located at Argonne National Laboratory. A bubble chamber is a detector filled with super-heated transparent liquid, used to detect electrically charged particles passing through the material. When high-energy charged particles pass through this material, they create an ionization track, vaporizing the liquid and leaving behind microscopic bubbles. There are other similar detector technologies like the cloud chamber, which results in a similar outcome, but uses supersaturated vapor in gas. Both types of experiments have good resolution, but can only reconstruct events in two dimensions [30]. Having reconstructed events in two dimensions instead of three loses valuable information about the kinematics of the interaction. In addition, these types of detectors fail when trying to scale-up to large detector sizes, which are needed for studying neutrino physics at the GeV level, and gaining new information in a reasonable time-frame.

3.1 Neutrinos in Matter

Neutrino interactions with matter can only be detected indirectly. Therefore, in order to develop better neutrino detectors it is important to revisit how neutrinos interact with matter.

Neutrinos have no electrical charge and only interact via the weak nuclear force. In most cases, a neutrino will interact through the exchange of a W or Z boson with the nucleus (or, less commonly, an electron) of a target atom, as discussed in Section 1.4. The final state particles from this interaction include those carrying electric charge, which will interact electromagnetically with other atoms as they propagate through the detector material. If a Z boson is exchanged with an atomic electron or nucleon (proton or a neutron), we call this a neutral current (NC) interaction.
Figure 3.1: This figure shows examples of Feynman diagrams for CC and NC neutrino interactions in matter. Analogous interactions occur for antineutrinos. For $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$, the t-channel $\nu_e e^- \rightarrow \nu_e e^-$ diagrams are replaced by an s-channel charged current process [3].

If a W boson is exchanged, we call this a charged current (CC) interaction. Figure 3.1 shows some examples of neutral and charged current interactions. Interactions with nucleons will dominate, since the neutrino interaction cross sections are proportional to the center-of-mass energy squared, $s \approx 2mE_\nu$, where $m$ is the mass of the target particle [3].

NC interactions can happen with any neutrino flavor. However, the observed appearance for CC interactions signal also depends on the whether the interaction is kinematically allowed. CC neutrino interactions are allowed if the center-of-mass energy is sufficient to produce a charged lepton and the final state hadronic system. The threshold is determined by the lowest $W^2$ process $\nu_l n \rightarrow l^- p$ and is only kinematically allowed if the lepton and proton are created at rest, such that:

$$E_\nu > \frac{(m_p^2 - m_n^2) + m_l^2 + 2m_pm_l}{2m_n}$$ (3.1)

Considering a laboratory frame with a neutron at rest, we can then say the neutrino threshold energies for CC interactions with a nucleon are:

$$E_{\nu_e} > 0, \quad E_{\nu_\mu} > 110 \text{ MeV}, \quad E_{\nu_\tau} > 3.5 \text{ GeV}$$ (3.2)
The nuclear binding energy must also be taken into account for electron neutrinos with energies of order few MeV.

Now that energy thresholds are known, it is important to define the measured mean energy loss, \( dE/dx \), of a charged particle interaction through matter. The mean energy loss to ionization per unit length of charged particles is described by the Bethe Bloch formula:

\[
\frac{dE}{dx} = K \frac{\rho Z}{A} \frac{z^2}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \gamma^2 \beta^2 W_{\text{max}}}{I^2} \right) - \beta^2 \right]
\]

\( W_{\text{max}} = \frac{2m_e c^2 \gamma^2 \beta^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \)

such that \( \rho \) is the density of the medium, \( Z \) and \( A \) are the atomic number and mass of the medium, \( z \) is the charge of the incident particle, \( \beta \) is the ratio of velocity to light \((v/c)\), \( \gamma \) is the Lorentz factor, \( I \) is the effective ionization potential, \( K \) is a constant, and \( W_{\text{max}} \) is the maximum energy transfer for a particle with mass \( M \) [40]. For a charged particle with kinetic energy such that \( \beta \gamma \sim 3 \), the rate of energy loss takes on a minimum value. Thus, charged particles in the range near this minimum are referred to as a minimum-ionizing particles (MIPs) [3].

It is now understood how neutrinos interact with matter, their energy thresholds for an interaction, and how to calculate the mean energy loss, depending on the medium it is interacting with. The next section explains why DUNE has chosen liquid argon as its detector medium.

### 3.1.1 Neutrinos in Liquid Argon

The use of noble liquids (rather than gas) is necessary in large-scale neutrino experiments. Noble liquids provide a large enough target mass for increased neutrino interaction probability and they have high electron mobility for being electro-positive. In addition, they are dielectric which allows for high voltages, they have adequate radiation lengths—the mean distance in which a high energy electron loses all but 1/e of its energy via bremsstrahlung.
Argon is the most abundant noble gas on Earth. Its liquid density, as shown in Table 3.1, is \(1.39 \text{ g/cm}^3\), makes it a good target for neutrino interactions, and is a copious source of scintillation light. At the same time, the extraction of argon from the Earth’s atmosphere has been industrialized, which makes it affordable to construct large detectors with it.

Assuming very good LAr purity, a typical MIP that traverses LAr will produce around 60,000 ionized electrons per centimeter. If we consider a particle depositing energy solely through ionization in LAr, the charge deposition over some distance \(\Delta x\) is proportional to the amount of energy deposited by the charged particle over that distance:

\[
\Delta Q = \frac{C}{W_{\text{ion}}} \Delta E
\]

\(\Delta Q\) = observed deposited charge [ADC], \(\Delta E\) = deposited energy [MeV]

\(C = \) charge calibration constant \(W_{\text{ion}} = \) ionization energy of LAr \((23.6 \times 10^{-6} \text{ MeV/e})\)

Further, if we consider the continuous limit and relate the observed charge deposition rate, \(dQ/dx\), to the true energy deposition rate, \(dE/dx\), at location \(x\), we can infer the \(dE/dx\) from the observed \(dQ/dx\). Therefore, the relation becomes:

\[
\frac{dQ}{dx} = \frac{C}{W_{\text{ion}}} \frac{dE}{dx}
\]

If we consider DUNE’s FD1-HD (mentioned in Section 2.5.1) as an example: given an electric field of 500 \(V/cm\), these electrons will drift toward the anode grid at a rate of 1.6 \(mm/\mu s\). Considering \(W_{\text{ion}}\) and \(C\) are known constants, we could calculate the energy deposition by collecting the charge. This is assuming pure LAr and no other physical effects—discussed further in Section 3.2.3.

It is now understood how neutrinos interact with matter and how to infer the energy deposition \((dE/dx)\), via the observed ionization charge. The next section will discuss how DUNE will use LArTPCs to collect this observed ionization charge.
3.2 Detecting Neutrinos in LAr

First proposed by Carlo Rubbia in 1977, who combined the idea of the gaseous Time Projection Chamber (proposed by David Nygren in 1974) with what was known about liquid-argon counters at the time, and developed the Liquid Argon Time Projection Chamber (LArTPC) concept [41]. The LArTPC follows the same concept of a bubble chamber, and has long been recognized for its potential for neutrino experiments. When a charged particle crosses the active LAr volume of the TPC, it leaves an ionization track, composed of ionized atoms and electrons. By applying a strong and very uniform electric field, the electrons will separate from the charged argon atoms and start to drift, parallel to the electric field.

3.2.1 Liquid Argon Time Projection Chamber

As mentioned in 2.5, there are two different types of FD modules, the Horizontal Drift (HD) and the Vertical Drift (VD); both modules based on the LArTPC and LAr Photon Detection (LArPD) concept. The next sections will discuss how the FD1-HD LArTPC and LArPD detects and processes these neutrino events. Figure 3.2 shows an example of an LArTPC, consisting of a cathode (left) and an anode (right). The cathode is biased negative, with a high potential, and the anode is set to ground. The result is an electric field that drifts ionized electrons, produced by high-energetic charged particles traversing LAr, toward the anode. The ionized electron signal is detected using a set of induction and collection wire planes that are wrapped around the Anode Plane Assembly (APA). The far right of the figure shows two 2D projections viewing the same track [42].

DUNE’s first full-size prototype, ProtoDUNE-Single Phase (SP)—further discussed in detail in Chapter 5—can be used to further explain looking at LArTPC interaction events. Figure 3.3 shows an example of what a real MIP interaction with LAr would look like in 3D space—here the MIP (muon) is traversing through one of the two TPCs in the ProtoDUNE-SP experiment [44]. This track reconstruction was made by collecting the electrons that were ionized by the interaction.
Table 3.1: This table shows LAr having the best feasibility; having a high density, which makes it a good target for neutrino interactions, and produces a copious source of scintillation light[43].

<table>
<thead>
<tr>
<th>Properties of noble liquids</th>
<th>Water</th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point [K] 1 atm</td>
<td>373</td>
<td>4.2</td>
<td>27.1</td>
<td>87.3</td>
<td>120</td>
<td>165</td>
</tr>
<tr>
<td>Liquid density [g/cm³]</td>
<td>1</td>
<td>0.125</td>
<td>1.2</td>
<td>1.39</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>Radiation length [cm]</td>
<td>36.1</td>
<td>755.2</td>
<td>24</td>
<td>14</td>
<td>4.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Scintillation Yield [γ/keV]</td>
<td>-</td>
<td>19</td>
<td>30</td>
<td>40</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>Scintillation λ [nm]</td>
<td>-</td>
<td>80</td>
<td>78</td>
<td>127</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>dE± dx [MeV/cm]</td>
<td>1.9</td>
<td>0.24</td>
<td>1.4</td>
<td>2.1</td>
<td>3</td>
<td>3.8</td>
</tr>
<tr>
<td>Abundance (Earth atm) [ppm]</td>
<td>25 × 10³</td>
<td>5.2</td>
<td>18.2</td>
<td>9300</td>
<td>1.1</td>
<td>0.09</td>
</tr>
<tr>
<td>Electron mobility [cm²/V·s]</td>
<td>-</td>
<td>&lt; 0.3</td>
<td>&lt; 0.01</td>
<td>~500</td>
<td>~1800</td>
<td>~2200</td>
</tr>
</tbody>
</table>

Recall from Section 2.5.1, ionized electrons drift toward the anode plane. Once at the anode, the free electron is transported through two wire planes and then collected on the last wire plane. This is done by having a differential potential between each wire plane, properly biasing the wires so electrons can be pulled through multiple (induction) planes without loss and be collected on the last one. This results in obtaining two induced signals and a collection signal that give two 2D-views of a track, as shown in Figure 3.4. Using these two views and the known electron drift velocity, since the electric field is controlled (as mentioned above), we can reconstruct a 3D track to nm resolution, as shown in Figure 3.3. Finally, the integrated charge of the signals allow us to calculate the deposited energy per unit track length and help us to identify the interacting particle, i.e., particle identification [45].

### 3.2.2 Scintillation Photons in LAr

LArTPCs provides excellent particle track resolution. However, determining the absolute position of an event interaction is difficult. Fortunately, another key principle of LAr is that it is an excellent
Figure 3.2: This figure shows an example of an LArTPC, which consists of a cathode (left) and
an anode (right). The cathode is biased negative, with a high potential, and the anode is set to
ground. The result is an electric field that drifts ionized electrons, produced by high-energetic
charged particles traversing LAr, toward the anode. The ionized electron signal is detected using
a set of induction and collection wire planes that are wrapped around the Anode Plane Assembly
(APA). The far right of the figure shows two 2D projections viewing the same track [42].

When a charged particle traverses LAr, argon dimers (Ar$_2^*$) are produced—two argon atoms
bounded together with a shared electron (in a Rydberg state). This excited argon dimer will then
radiatively decay back to its ground state, reverting back to two argon atoms and emitting a 128 nm
photon. This process of a photon being emitted via charge particle interaction is defined as LAr
scintillation.

$$Ar \rightarrow Ar^* \xrightarrow{+Ar} Ar_2^* \rightarrow 2Ar + \gamma$$  (3.6)
Figure 3.3: This figure shows an example what a real MIP interaction with LAr would look like in 3D space—here the MIP (muon) is traversing through one of the two TPCs in the ProtoDUNE-SP experiment [44].

\[ \text{Ar} \rightarrow \text{Ar}^+ + e^- + e^\text{recomb}_2 \rightarrow 2\text{Ar} + \gamma \]  

(3.7)

There are two of these scintillation mechanisms that happen in LAr: (1) Self-trapped exciton luminescence (2) Recombination luminescence. The Self-trapped exciton luminescence case starts with an excited argon combining with another argon atom to form an excited argon dimer (Ar$_2^*$). In the recombination luminescence case, argon ions will gather together and form an ionized dimer (Ar$_2^+$). Then, if the electric field is not high enough to completely separate the electron, the recombination process will generate an excited argon dimer (Ar$_2^*$). Both mechanisms result in the same scintillation process and is shown in Figure 3.5 and equations 3.6 & 3.7 [47, 46].

There are two states in which the argon dimer can exit before it decays, a singlet state and a triplet state. The emission lifetime of the singlet state is fast of 6 ns, while the emission lifetime
Figure 3.4: This figure shows an example of how an LArTPC collects ionized electrons as they drift toward the anode plane. Once at the anode, the electron is transported through two wire planes and then collected on the last wire plane. This is done by having a differential potential between each wire plane, properly biasing the wires so electrons can be pulled through multiple (induction) planes without loss and be collected on the last one. This results in obtaining two induced signals and a collection signal that give two 2D-views of a track, shown here as the *x-view* and *y-view* [45].

The triplet state is *slow* of $\sim 1500$ ns. The latter value has been verified by our group [48]. The prompt light from the singlet state is what has been defined as $t_0$. The drift time can then be calculated by the difference of the time of the charge readout minus $t_0$. This improves the spatial resolution along the drift direction to $< 1 \text{ mm}$.

The scintillation light signal in LAr can be described by a combination of two exponential decay distributions, as a function of time:

$$S(t) = A_s e^{-t/\tau_s} + A_T e^{-t/\tau_T}$$  \hspace{1cm} (3.8)

such that $S(t)$ is the time evolution signal, $A_s$ & $A_T$, and $\tau_s$ & $\tau_T$ are the amplitudes and time
Figure 3.5: This figure shows an example of LAr scintillation. An argon dimer ($Ar_2^*$) is created and will then radiative decay back to its ground state, reverting back to two argon atoms and emitting a $128\ nm$ photon. There are two of these scintillation mechanisms that happen in LAr: (1) Self-trapped exciton luminescence (2) Recombination luminescence. This image was taken from a talk, given by B. Jones [46].

constants for the singlet ($s$) and triplet ($T$) decay states, respectively.

Depending on the ionizing particle, these decay states have been found to be in different amounts [47]. Figure 3.5 can be used as a reference of different ratios of the $fast/slow$ components. The ratio of $fast/slow$ can be related to the ionization density of LAr and dependent on ionization particle. For electrons this ratio is 0.3, for alpha particles 1.3, and for neutrons 3.0 [49]. It should also be noted that the fast component can be used as a veto for cosmic ray events or as a trigger for non-beam events, such as supernova bursts and nucleon decay.

It is important to reiterate that LAr is highly transparent to its own scintillation light. Therefore, this prompt scintillation light signal can be detected and given a timestamp of the event interaction—we call $t_0$. Relative to the drift charge, these photons travel almost instantaneously
and can help correct the time and spatial localization of such an event.

### 3.2.3 Correcting for Physical Effects

The last sections discussed how to measure and detect the energy deposition from a charged particle interaction via charge and light. However, these calculations assumed pure LAr with no additional physical effects. Therefore, we must consider some known physical effects, such as LAr purity, electron-ion recombination, space charge effects, diffusion, electron attenuation, and other physical effects.

Ultra-pure argon is very transparent, but *dirty* argon is not. All liquid argon will have some traces of impurities, so it is necessary to understand and be able to measure this. Contaminants such as oxygen and water can essentially capture the ionized electrons drifting toward the anode, increasing in probability with longer drift distance. In addition, nitrogen can quench scintillation light during the scintillation process. Quenching shortens the long time constant and reduces the total scintillation yield. For these reasons, it is necessary to contain contamination of nitrogen $< \text{ppm}$, and oxygen and water $< \text{ppb}$ [50, 46].

Electron-ion recombination is an effect sensitive to the amount of charge deposited, the size of the drift electric field, and the density of the medium. The dominant effect is caused by ionized electrons recombining with their parent ion. Fortunately, this recombination effect has been well studied for LArTPCs in ICARUS & ArgoNeut experiments [51, 52].

The accumulation of argon ions leads to position-dependent drift E-field distortion, which compounds the recombination effect. This in turn leads to ionization electrons being pulled near the middle of the detector and creating an offset in the observed hit positions. This has been studied in the MicroBooNE experiment [53] and is well understood.

There are other minor effects still being studied, such as a diffusion process leading to *leaking* charge, hardware & mechanical issues, and long-term temperature effects. Going forward, DUNE
is in the process of further developing these models, that have been studied by other experiments, for the Near and Far Detectors, with the goal in mind of maintaining these effects low enough to ensure a electron drift lifetime of $3\, ms$.

Combining the collection of both charge and light, we can determine the absolute position of an event interaction and understand its total energy deposition ($\gamma s + e^- s$). In addition, scintillation light can also provide information on rejection backgrounds, calorimetry, nucleon decay, reconstructing neutrinos from supernova bursts, and other cosmological sources. Understandably, photon detection is complimentary to LArTPCs and is critical for the DUNE physics program.
Chapter 4

Developing a UV Lens

The main topic of this thesis is on scintillation photon detection in LArTPCs and how it will contribute toward understanding neutrino physics, as an element of the DUNE experiment. Throughout my years as a graduate student at Indiana University, my primary work has contributed to the research and development on all components regarding the Photon Detector System (PDS) for the DUNE Far Detector modules; the main objective being to optimize our physical understanding of scintillation light in LAr.

My work was carried out in the context of DUNE FD1-HD PDS. However, the PDS for DUNE FD2-VD is very similar and based on the knowledge and experience of FD1-HD. This chapter will focus on the work I have done toward the DUNE FD1-HD PDS. Specifically, it will focus on my contributions to each sub-component of the PDS technology, and how they have led to technological advances in scintillation light detection in LAr, and the overall understanding of the challenges for instrumentation.

As discussed in Chapter 2.5, the PDS for DUNE’s FD1-HD is critical for the DUNE physics program. Detecting the time of an event’s prompt scintillation signal, $t_0$, improves the TPC’s spatial localization along the drift direction to mm precision and can improve event time resolution to the $\mu$s level or even better. Moreover, it allows for accurate event topology and energy deposition determination by accounting for the attenuation of the ionization and by augmenting the signal due to electronegative contaminants. In addition to improving the resolution of reconstructed particle trajectories, the observation of scintillation signal can allow us to reject backgrounds to nucleon decay, and better reconstruct neutrinos from supernova bursts and other cosmological sources.

Scintillation light produced in LAr has a wavelength of 128 nm, which is too short in the spectrum to be directly detected by a vast majority of current photosensors. Therefore, a design
needs to be made to convert this vacuum ultra violet (VUV) light to visible wavelengths, in order to be observed efficiently. For the DUNE FD1-HD, the photon detector (PD) modules view the LAr volume through each face of an APA, each held within an APA internal support structure. Photon detector modules are affixed to ten support structures (internal rails) mounted between the two sets of wire planes on either side of an APA. Thus, PD modules are arranged as long, thin bars oriented horizontally (\( \hat{z} \) direction) perpendicular to the \( \hat{x} \) drift direction and separated by about 60 cm in the \( \hat{y} \) vertical dimension.

Therefore, the design is constrained to: (1) the PDS must be sensitive to low levels of light (0.5 photo-electron/MeV of energy deposition); (2) have a minimum timing resolution of 100 ns; (3) it must not interfere with the operation of the TPC and fit within the APA as just described; (4) it must be implemented so as to minimize cost, while maximizing light detection efficiency.

Each of the PDS detector technologies considered for DUNE will be described in Section 5.3. All of them use similar SiPM photosensors and readout electronics. Therefore, the next sections will describe the features of the chosen photosensor for DUNE, as well as the PDS signal processing and digitization hardware, and PDS triggering. The remaining of the chapter will focus on the PDS technology developed at IU, and the program of testing and development that contributed to LAr PD technology optimization.

4.1 Photosensor Readout and Triggering

A silicon photomultiplier (SiPM) is an array of high gain microcells that require much less space than traditional LAr VUV-photosensors, such as PMTs, yet can still detect single-photon emissions with a high photon detection efficiency (PDE). They possess comparable gains to a PMT (\( \sim 10^6 \)), but require a much lower operating voltage, 20-60 V, and much less physical space. In addition, they are low cost and do not require much warm-up time in cryogenic temperatures, as needed by the traditional PMT. This novel technology has made it an excellent choice for the photosensors
used in DUNE. Thus, each of the PDS detector technologies use SiPMs. The manufacture type, however, is still being explored. In this chapter the SensL SiPM is used, as it has a long history of producing quality products. Though, you will see in Section 4.4, that different SiPM types are tested as contenders.

In the design for each PDS readout system, unamplified signals are transmitted from the LAr volume to the outside of the cryostat, where they are processed and digitized using a custom signal processor. The next two sub-sections discuss more about the photosensor and the signal processing electronics utilized in the experimental work described in this thesis.

4.1.1 Photosensors

For a SiPM, each microcell is composed of a series combination of a silicon avalanche photodiode (APD) and a “quenching” resistor. All microcells are connected in parallel, therefore, they have two contacts: a common cathode and anode. A photon incident on the active area is absorbed within the APD, creating an electron-hole pair. Under reverse bias, one of the two charge carriers drifts into the microcell’s high-field region where it triggers an avalanche, subsequently quenched by the resistor. The result is a current pulse from the anode, proportional to the the number of photons collected, recorded in photo-electrons (PEs). Figure 4.1 illustrates a digitized raw signal from a SensL SiPM shown in black, and a noise-filtered waveform shown in red.

The exact shape of the waveform depends on the electrical properties of the microcell, the applied bias voltage (specifically the overvoltage relative to the SiPM breakdown voltage), and the analog to digital characteristics of electronics. For a typical single SiPM, the rise time is on the order of 10 ns, and the fall time is on the order of half a microsecond. Both are independent of overvoltage, but increase with the cross section of a microcell. The amplitude of the current pulse is proportional to the over-voltage and inversely proportional to the quenching resistance. The area under the pulse, expressed in number of electrons, equals the gain, which is linearly
Figure 4.1: Sample waveform of a single photon digitized signal of a SiPM. The digitized raw signal shown in black, and a noise-filtered waveform shown in red proportional to the product of the overvoltage and the cross section of a microcell (for the optimal overvoltage region). The overvoltage is the key parameter for controlling the operation of a SiPM, and is defined as the difference between the applied reverse-biased voltage (VBIAS) and breakdown voltage (VBD). An optimal value is dependent on temperature, and is discussed in more detail in appendix A.

4.1.2 Photon Detector Readout Electronics

The PDS readout system transmits unamplified signals from the SiPMs in the LAr volume to the outside of the cryostat, via a long multi-conductor Cat6 cable. These Cat6 cables carry the analog signal to a custom module for processing and digitization, called an SiPM Signal Processor (SSP), developed and manufactured by Argonne National Laboratory [54].

An SSP module consists of 12 individual readout channels packaged in a self-contained 1U rack module [55]. Each channel contains a fully-differential voltage amplifier and a 14 bit, 150 MHz
analogue-to-digital converter (ADC) that digitizes the waveforms received from the SiPM arrays. The front-end amplifier is configured as fully-differential with a high common-mode rejection, and receives the SiPM signals into a termination resistor that matches the characteristic impedance of the signal cable. The processing of the data is performed by a Xilinx Artix-7 Field-Programmable Gate Array (FPGA) and is stored in pipelines in the SSP for up to 13 µs for a single output, per channel. The FPGA implements an independent Data Processor (DP) for each channel and incorporates a leading edge discriminator for detecting events and a constant fraction discriminator (CFD) for sub-clock timing resolution.

![Diagram](image)

Figure 4.2: This diagram shows the operational schematic of how a SSP manages itself, and how it interfaces with the trigger, DAQ, and timing systems [23].

Each channel can be individually triggered by any of the following: a periodic timestamp trigger, an SSP-internal trigger based on a leading-edge discriminator local to the individual channel, or an SSP-external trigger from an external source. If an SSP trigger is present, the channel will produce a data packet consisting of a header and a waveform of predefined length, which comprises a series of ADC values. The header contains bookkeeping information (e.g., module and channel numbers,
timestamps, trigger type) and some calculated ADC values for each waveform. The SSP trigger system is distinct from the global trigger, therefore, the unit of data produced when a SSP channel triggers is called a packet; the term trigger here refers to global triggers only.

In general, an SSP fragment will contain a fixed 12 packets with identical timestamps corresponding to the trigger time, one for each channel, and also an arbitrary n-number of additional packets generated when a channel’s discriminator fires (i.e. SSP internal-triggers). It should be expected that a different number of packets will be observed for each channel within a given fragment. An operational schematic of the SSP is shown in Fig. 4.2.

4.1.3 SiPM Studies

During my first year of research at Indiana University, my research focused on SiPM characterization and passive ganging studies. Tests were conducted locally at IU, using customized darkbox and cryogenic dewar setups. Initial single SiPM + signal degradation studies were made using a small dewar filled with \( \text{N}_2 \), contained in a light-tight darkbox. A detailed description of the performance of passively ganging 3 and 6 SiPMs relative to a single SiPM readout is discussed in detail in appendix A and will be described briefly here.

Passive Ganging Studies

The idea for passively ganging channels—connecting signals in parallel—is to reduce the number of readout channels needed, given a fixed photosensor readout active area, in order to substantially save on costs. Passively ganging channels decreases the number of total electronic cables and channels needed, while using SiPMs that are already commercially available. These factors allow us to maximize detector coverage, while still maintaining DUNE’s PDS requirement of 0.5 PE/MeV, all at a much lower cost for the PDS. Thus, studies to determine the optimal level of ganging were undertaken.
Figure 4.3: This figure shows the setup used in the IU testbed passive ganging experiment. The dewar, containing the different passively ganging schemes (right) —1-SiPM, 3-SiPM, & 6-SiPM— was placed inside a light-tight dark box (left). The analog SiPM signals were transmitted via Gore shielded twisted pair cables to a SSP for digitization and processing.

SiPM dark rates are on the order of 10Hz at LAr temperatures. Therefore, to test low level signals at minimal cost, and without introducing scintillation light, liquid nitrogen (LN2) was used instead of LAr to keep electronics cold. In regards to light, the major difference between the LN2 and LAr is that LN2 does not generate scintillation light; the minor difference being the evaporation temperature between LN2 and LAr, 77 K vs 87 K, respectively. To run dark measurements, the dewar was placed inside a light-tight dark box, transmitting the analog SiPM signals via Gore shielded twisted pair cables, as shown in Figure 4.3.

Figure 4.4 shows an example of a photo-electron (PE) peak distribution of a single SensL SiPM. Figures 4.5-4.7 shows an average 1-PE (2-PE for 6-gang) waveform and how the signal shape varies depending on how many SiPMs are ganged. The idea is that for any number of ganged SiPMs, the
Figure 4.4: This is an example plot of the SSP’s peakSum variable for all collected waveforms from triggers and pulses for a single run, with a Gaussian fit over a 1 PE region (Peak ± 2 ADC).

charge for a single PE should remain unchanged. However, the shape, mainly rise and fall times, changes due to the increase of capacitance.

A summary of the results for the study are shown in tables 4.1 - 4.3. The tables show that the rise time, decay time, and peak ADC/PE are strongly correlated with the number of SiPMs passively ganged together. As the number of passively ganged SiPMs increases, both rise and decay times increase, while ADC/PE decreases. In addition, the outside cables that were tested both in

<table>
<thead>
<tr>
<th>SiPM</th>
<th>1 PE</th>
<th>2 PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Individual</td>
<td>20.3</td>
<td>13.4 ± 0.5</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>9.5</td>
<td>19.0 ± 0.6</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>5.3</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.1: Mean Waveform Parameters for 10 m Cables
Figure 4.5: This is an example of an averaged 1 PE waveform for a single SensL SiPM, with 10 m cable, showing the line from which the rise time was determined (red), the falling edge fit used to determine the decay time (red), and the determined amplitude (in green).

Figure 4.6: This is an average 1 PE waveform, with 10 m cable, for a passive gang of 3 SensL SiPMs. Notice that the ADC/PE has dropped by about a factor 2 when compared to an individual SiPM and that the rise and decay time has increased.
Figure 4.7: This is an average 2 PE waveform, with 10 m cable, for a passive gang of 6 SensL SiPMs (1 PE is buried in the baseline noise). We can see that the ADC/PE has dropped again by about a factor of 2 with respect to Figure A.5, with the rise and decay time further increasing.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>1 PE</th>
<th>2 PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Individual</td>
<td>19.5</td>
<td>14.7 ± 0.5</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>9.4</td>
<td>22.9 ± 0.9</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>5.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2: Mean Waveform Parameters for 20 m Cables
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Individual</td>
<td>17.9</td>
<td>18.6 ± 1.1</td>
<td>490</td>
<td>14.7 ± 0.9</td>
<td>482</td>
<td>2.55 ± 0.40</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>8.6</td>
<td>27.1 ± 2.1</td>
<td>877</td>
<td>20.3 ± 1.4</td>
<td>866</td>
<td>2.63 ± 0.29</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>4.8</td>
<td>-</td>
<td>-</td>
<td>23.5 ± 3.1</td>
<td>1233</td>
<td>2.67 ± 0.29</td>
</tr>
</tbody>
</table>

Table 4.3: Mean Waveform Parameters for 40 m Cables

room and LN2 temperature were found to be independent of temperature, but I found that cable length is positively correlated with baseline noise. Further discussion on this is found in a technical document I wrote for these studies [56]. As mentioned, DUNE’s goal is to detect clean 1-PE signals. Therefore, for the Indiana University (IU) PDS design, we optimized our passive-ganging to 3-SiPMs per channel.

### 4.2 Indiana University PDS Technology

The IU PD module design was developed by our group at Indiana University [57], and is now called the Double-Shift Lightguide. This technology, originally designed similar to the Dip-Coated Lightguide technology (see Section 5.3.1), has evolved to enhance reproducibility, as well as separating the conversions from UV light to visible wavelengths [48]. As shown in Figure 4.8, VUV 128 nm scintillation light strikes a TPB surface-embedded acrylic plate and converts the VUV light to the visible-blue (420-450 nm). Once converted, the transmitted photons are subsequently absorbed by a commercial lightguide and are again wavelength shifted to the visible-green (480-510 nm). The light is then guided, via total internal reflection, down to one end where they are read out by a photosensor array.

The Double-Shift Lightguide solves two issues that the original design had: (1) reproducibility of coating the lightguide with a wavelength-shifting (WLS) solution. A special arm-device was con-
Figure 4.8: This cartoon shows the IU PD module design. This technology was originally designed similar to the Dip-Coated Lightguide technology, however, has evolved to enhance reproducibility, as well as separating the conversion from UV light to visible wavelengths. As shown in the figure, the VUV 128 nm scintillation light strikes a TPB surface-embedded acrylic plate and converts the VUV light to the visible-blue (420-450 nm). Once converted, the transmitted photons are subsequently absorbed by a commercial lightguide and are again wavelength shifted to the visible-green (480-510 nm). The light is then guided, via total internal reflection, down to one end where they are read out by a photosensor array.

4.2.1 Wavelength Shifting Plates

The outer WLS material consists of acrylic radiator plates that completely cover the lightguide and are placed end-to-end. The plates are commercially made by McMaster Carr and are 1/16 inch acrylic plates, laser-cut in pairs at Fort Collins Plastics in Fort Collins, CO. For these plates
to become a WLS material, the plates are then coated manually using a Binks high-volume lower pressure sprayer system at Indiana with a WLS solution, consisting of 5 gm of scintillation grade (>99%) TPB to 1,000 gm of dichloromethane. Once the plates are coated, they are annealed in a vacuum oven at 80°C, which is the temperature just below the melting point of the acrylic plate. The annealing fuses the TPB into the acrylic, ensuring that it will not separate or precipitate due to aging or cryo-cycling in LAr.

4.2.2 Wavelength Shifting LightGuide

The second WLS material and primary lightguide is made from special commercial crosslinked polystyrene, EJ-280PSM, produced by Eljen Technology. The polysterene is cut into bars (of appropriate length) and both major faces clear as-cast and all edges diamond-milled. The advantages of using an unaltered lightguide, compared to the Dip-Coated Lightguide, are that uniformity across the bar is significantly enhanced, as well as reproducibility for all modules; allowing for a more uniform PD detector, with excellent optical properties leading to long (>2 m in LAr) attenuation lengths.

In summary, the VUV 128 nm scintillation light strikes a TPB surface-coated acrylic plate. The TPB coating efficiently absorbs the VUV light and reemits visible-blue photons, typically ranging from 420-450 nm. Once converted, many of the photons are subsequently absorbed by the EJ-280PSM commercial lightguide and are again wavelength shifted to the visible-green, typically ranging from 480-510 nm. Figure 4.9 shows the emission spectrum for the WLS radiator plates and the emission spectrum for the EJ-280PSM lightguide. The twice converted photons are then propagated via total-internal-reflection down to one end of the lightguide, where they are read out by a photosensor array readout [57].
Figure 4.9: The left figure shows the emission spectrum for the TPB-coated radiator plates and the well-matched lightguide absorption spectrum. The right figure shows the emission spectrum for the EJ-280PSM lightguide and the photosensor (SiPM) photon detection efficiency (PDE). This design allows for a moderate 128 nm photon detection efficiency, while deconvolving the 2-fold WLS components for production and quality control [57].

4.3 Blanche Experiment

Though many iterations (tests/experiments) led to the development of Indiana University’s Double-Shift Lightguide technology, the first prototype aimed for DUNE was tested using the LAr facilities at the Proton Assembly Building (PAB) at Fermilab. In this section I will briefly explain the experimental setup and results of the Blanche experiment, with its main objective to determine the IU Double-Shift Lightguide efficiency. For further details regarding this experiment, I encourage the reader to reference our published paper [57].

4.3.1 Experimental setup

This experiment tested the first two PD module prototypes in LAr using the ∼ 600 L dewar, named Blanche. Each module was ∼ 76 cm in length, containing one WLS lightguide and four WLS plates on each face of the module. These modules were mounted on a metallic frame and suspended from the flange of the dewar, as shown in Figure 4.10. For simplicity of our data analysis, we
Figure 4.10: This figure shows a schematic depiction of the first two Double-Shift Lightguide prototypes being tested with the Blanche experiment [57].

*cut* the dewar in half via this metallic frame containing our PD modules. Since the Double-Shift Lightguides have the capability to view the detector on both sides, we referred to the two *cut* sections as being the “front” & “back” side on the dewar. The scintillation signals produced in the LAr (described in Section 3.2.2) were collected by the Double-Shift Lightguides, using 8 single SiPM channels, and were read out using an SSP, as described in Section 4.1.2.

Once the modules were inserted, the dewar is then vacuum sealed and purged before filling with LAr. Filtration on the input line removes most of the remaining $O_2$ and $H_2O$ contamination from the ultra-high-purity LAr used. In addition, contamination monitors recorded $O_2$, $N_2$, and $H_2O$ levels. A condenser was then connected to ensure the level of LAr level was stable throughout the experiment. Concentrations of $O_2$, $H_2O$, and $N_2$ contamination during this run were found to be $\sim 30$ ppb, $\leq 5$ ppb, and $\sim 80 - 90$ ppb, respectively. These contamination levels are within acceptable levels for scintillation studies [58].
Figure 4.11: This figure shows a schematic depiction of the triggering setup for the Blanche experiment, using two hodoscopes and two scintillator paddles as a four-fold coincidence trigger, detecting a through-going muon [59].

The external source trigger was composed of a 4-fold coincidence logic trigger, shown in Figure 4.11. Two hodoscope arrays, formally from the CREST experiment [60] were placed on each side of the Blanche dewar. The hodoscope array is a set of barium-fluoride crystals, each with a corresponding PMT, arranged in an 8x8 pattern. Between each hodoscope and the dewar was a scintillator paddle. The requirement for a muon trigger was that a muon needed to trigger in the following logic: hodoscope → paddle → through dewar → paddle → hodoscope. Following these triggers, single-track events are selected from this sample by requiring only one PMT in each hodoscope array to have fired along with the corresponding scintillator paddles.
Table 4.4: This table shows the determined fit parameters of the transport function (eq. 4.1), using simulation data described in our paper [57].

<table>
<thead>
<tr>
<th></th>
<th>$A/(A+B)$</th>
<th>$x_{sh}$ [cm]</th>
<th>$A/(A+B)$</th>
<th>$x_{lng}$ [cm]</th>
<th>$(\chi^2/dof)_{sim}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport function</td>
<td>0.29</td>
<td>4.30</td>
<td>0.71</td>
<td>225</td>
<td>448/296</td>
</tr>
</tbody>
</table>

4.3.2 Data Analysis and Results

The total duration of this experiment lasted about two weeks during the fall of 2016. For reasons described in [57], only data from one of the front-side PD modules were used for the analysis. The calibration data was taken by random-trigger data taking and calibrated similar to Section 4.1.3. After each channel was properly calibrated, the seven channels were summed together, giving the total number of PEs detected for a given trigger, called $N_{det}$. Many filters were used to obtain a clean dataset of single minimum ionizing muon tracks, totalling to $\sim$ 11,000 tracks used for the analysis and results.

A Monte Carlo simulation was developed by our IU group in order to simulate the produced scintillation light produced by cosmic ray muons (treating them as MIPs) and the ray-tracing of the scintillation photons within this LAr dewar. The simulation consisted of a track-trajectory of the MIP, based on a PMT-hit from each of the hodoscopes. Following this track, the simulation assumed a minimum ionizing muon would deposit 40,000 photons/MeV [61]. This allowed the simulation to produce photons at a certain line-segment trajectory, and then trace each photon within the dewar, accounting for the proper geometry, photo-absorption, reflectivity, Rayleigh scattering, and detection.

For each simulated track, the number photons incident on the photon detector is propagated through the detector to the readout end, called $N_{exp}$. This propagation calculation was based on further studies done at IU, where a determined transport function was calculated for these
Two additional selection cuts were made. (1) To exclude spurious triggers with no activity in the dewar, PD1 and PD2 were each required to collect at least 10 photoelectrons (PE) from the track. (2) To exclude triggers from high energy events unlikely to be minimum ionizing muons, events with relatively high energy deposition in the hodoscope crystals were removed. There were 11,223 tracks analyzed that passed the cuts.

The waveforms collected by each SiPM in the track were pedestal subtracted and summed from 0.7 \( \mu s \) before the trigger until 11 \( \mu s \) after the trigger. The result is the total number of ADC counts in the track for each SiPM. For the

\[ \text{Integrated Signal [PE]} \]

\[ 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \quad 1600 \quad 1800 \quad 2000 \]

Tracks

\[ 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \quad 450 \quad 500 \]

All triggers

Selected tracks

Rejected triggers

Figure 10: The histograms of the integrated PE from all preselected track-like triggers. Also shown are the histograms for the tracks passing all cuts and the triggers excluded from the data set. The “Selected tracks” are the cosmic muon data set analyzed.

calibration of ADC counts to PE, a data set was recorded in the “self-triggered mode”, in which all signals above threshold were recorded with minimal cuts, and a histogram was filled that showed the separation between the single PE peaks. This separation provides the PE calibration. The calibrated PE counts in each SiPM were then summed. Fig. 10 shows a histogram of the integrated PE from all triggers. Also shown in the figure are the histograms for the tracks passing all cuts and the triggers excluded from the data set. The integrated number of PE for the selected tracks, \( N_{det} \), makes up the cosmic muon data set

Figure 4.12: This figure shows the integrated signals for all preselected track-like triggers used for the analysis of the Blanche experiment [57].

photons [57]. The transport function models:

\[ f(x) = A e^{-x/x_{sh}} + B e^{-x/x_{lng}} \quad (4.1) \]

calculating the probability that a photon absorbed by the wavelength shifter in the lightguide reaches the readout end, as a function of its starting distance. Table 4.4 shows the determined fit parameters [57].

Figure 4.12 shows the integrated signals for all preselected track-like triggers used for the analysis of the Blanche experiment. Based on the information described above, the characterization of the efficiency for this experimental setup can be calculated at the readout end by the fraction \( N_{det}/N_{exp} \), including corrections for afterpulsing and cross-talk (\( \sim 1.25\text{PE/Photon} \)) [57]. For a detailed example of how we determine afterpulsing and crosstalk calculations, please refer to Section 7.4.5. Finally, to extrapolate this efficiency for a full-scale DUNE PDS module, a factor of 12/8 was applied, since the module for DUNE will have 12 photosensors at the readout end, instead of the 8 used in this experiment (see Section 5.3.2). Including these corrections, the determined
efficiency was calculated to be 0.41% and the readout end of the detector. Figure 4.13 shows the efficiency of the Double-Shift Lightguide both using laboratory measurements and the Blanche analysis; describing the efficiency fall-off based on said transport function and where the efficiency of 0.41% is at x = 0.

Figure 4.13: This figure shows the efficiency of the Double-Shift Lightguide. The Blanche results (blue) are compared to laboratory measurements (grey), both describing the efficiency fall-off based on the transport function. The efficiency of the readout end (x = 0) is 0.41%. Results shown incorporate corrections and extrapolation for an ideal DUNE-size PD module [57].

4.4 TallBo Experiments

The knowledge and expertise gained from both the Blanche experiment and the ganging studies (discussed in Section 4.1.3) led our group to continue to optimize our IU technology. Two experiments followed, using a similar dewar at Fermilab, called the TallBo dewar. These experiments took place in 2017 and 2018, and studied ganged-SiPMs for the readout end of our detectors, increasing photon detection efficiency, and validating the performance of module reproducibility.
For these TallBo experiments, I was lead for component selection studies used in the experiment, installation and commissioning of the experiment, and running the day-to-day operations. Each of these experiments led to a co-authored paper [62, 63] and will be briefly described in the following section.

Figure 4.14: This figure shows a 3D schematic depiction of the placement of 3 PDS modules relative to the hodoscope positions, removing the cryostat for a better visual. The actual setup is similar to 4.11.

4.4.1 Experimental setup

Figure 4.14 shows a 3D cartoon of the placement of PDS modules relative to the hodoscope positions, removing the cryostat for a better visual. The actual setup for both experiments is similar to the Blanche setup, shown in Figure 4.11, and described in Section 4.3.1. Minor differences include: (1) that the TallBo dewar holds $\sim 460L$ of LAr (2) the modules tested were 165cm in length (3) between all three experiments, the PD modules and photosensor readout ends were altered/upgraded.
The same idea of cutting the detector into two sections, labeling “front” and “back” side of the dewar, was used. Purity was monitored, making sure the $O_2$, $N_2$, and $H_2O$ levels were at acceptable conditions for LAr scintillation for all experiments.

Figure 4.15: This figure shows a look inside of the physical detectors for the 2017 TallBo experiment, where the Double-Shift Lightguides are shown on left and middle, and the ARAPUCA module on the right of the left panel. The right panel shows an outside view of the physical dewar.

The first TallBo experiment was in fall of 2017, which tested the next version of the Double-Shift Lightguide. In addition, we had the opportunity to test another DUNE-PDS prototype, called the ARAPUCA module—later described in detail in Section 5.3.3. The TallBo frame, shown in Figure 4.14, contained two Double-Shift Lightguides and one ARAPUCA module, containing two sets of four ARAPUCA cells. A look inside of the physical detectors is shown in Figure 4.15, where the Double-Shift Lightguides are shown on left and middle, and the ARAPUCA module on the right of the left panel. The right panel shows an outside view of the physical dewar.
The second TallBo experiment was in fall of 2018, which tested the relative response of passive and active ganging of SiPMs, called MPPCs (multi-pixel photon counters), as well as possible module degradation due to thermal cycling. For this experiment we had the opportunity to test yet another DUNE-PDS prototype, called the Dip-Coated Lightguide—later described in detail in Section 5.3.1. Figure 4.16 shows the PD modules inserted into the Tallbo dewar, where the Double-Shift Lightguide is shown in the middle, and the Dip-Coated Lightguide on the right.

Figure 4.16: This figure shows a visual of the PD modules tested in the 2018 TallBo experiment, where the Double-Shift Lightguide is shown in the middle, and the Dip-Coated Lightguide on the right.

4.4.2 Absolute Efficiency Results

The absolute efficiency of the ARAPUCA module was determined in the 2017 TallBo experiment, including publishing a co-authored paper [63]. Unfortunately, the Double-Shift Lightguides were not able to be properly calibrated, due to exceeding the limit of ganging SiPMs—we found that
Figure 4.17: This figure summarizes the calibration procedure and performance of the ARAPUCA module for the 2017 TallBo experiment. Left: example waveform of an ARAPUCA channel. Middle: shows a clean separated charge distribution using dark runs. Right: shows a nice linear response for detected PEs [63].

12-ganged SiPMs for both passive and active ganging led to a mismatch in capacitance with the signal processor at that time. Something that has now been taken into account for future ganging studies. However, the Double-Shift modules were very useful in identifying through-going muons for proper trigger events, as well as determining which side (front or back) the muon was traversing. Combining with the single-faced ARAPUCA design, allowed the offline analysis to separate events from background rather easily.

The performance of the ARAPUCA device was determined by analyzing 8 weeks of cosmic ray data in the fall of 2017, using the TallBo LAr cryostat at the PAB facility. Figure 4.17 summarizes the calibration procedure and performance of the ARAPUCA module. Left: example waveform of an ARAPUCA channel. Middle: shows a clean separated charge distribution using dark runs. Right: shows a nice linear response for detected PEs.

Figure 4.18 shows a comparison for two light patterns the ARAPUCA module tested, where the amount of light expected to arrive in each ARAPUCA cell (red), the number of detected photo-electrons (black), and the ratio between them (blue). The determined efficiency for an individual ARAPUCA cell was determined to be $0.60 \pm 0.02\%$ [63].
4.4.3 Response of Two Lightguide and Two Readout Technologies

Learning from our unfortunate experience with the Double-Shift readout response from the previous TallBo experiment (Section 4.4.2), this experiment tested the relative response of passive and actively ganging 12 Hamamatsu MPPCs. In addition, possible module degradation was tested by thermal cycling the detectors, via exchange of LAr in the dewar. The results for this experiment is discussed in our published paper [62].

Figure 4.19 shows an example of an averaged Passive (left) and Active (right) waveform. Parallel ganging MPPCs (photosensors) increases the output capacitance, proportional to the number of MPPCs connected in parallel, but leaves the MPPC bias voltage unchanged. The larger capacitance reduces the signal to noise (SNR), but the integrated signal from the 12 MPPCs on the board remains constant. The limiting factor of increasing capacitance is when the SNR reduces low enough to where it starts to blend in with the baseline noise. This is particularly important for week signals/events.

Active ganging adds signals without increasing the capacitance. However, active ganging has its own caveats. As shown in Figure 4.19, the active ganging of 12 MPPCs introduces a significant
Figure 4.19: This figure shows a look inside of the physical detectors for the 2017 TallBo experiment, where the Double-Shift Lightguides are shown on left and middle, and the ARAPUCA module on the right of the left panel. The right panel shows an outside view of the physical dewar.

overshoot (undershoot relative to the baseline). This overshoot artifact is most likely the result of mismatched impedance between the readout board and signal processor. The trouble then comes when determining the total charge collection of each waveform and thus, the number of photons collected. For this analysis, the choice was made to integrate the waveforms only out to the overshoot.

It was found that the relative efficiencies of both technologies is best obtained from the passive ganging boards. Further, the analysis suggested that the Double-Shift Lightguide was \( \sim 16\% \) more efficient than the Dip-Coated Lightguide [62]. Future efficiency calculations, shown in Section 7.5.2, will corroborate this result.

The analysis also showed that there was a drop-off in the light yield seen in both Double-Shift and Dip-Coated technologies, after the dewar was emptied of LAr and then refilled. Though conjecture, the cause of degradation seemed to be the result of either thermal cycling (all components included) or different traces of other dopants between each LAr fill, such as xenon, which could alter the light yields. Further discussion is talked about in our published paper [62].
Chapter 5

ProtoDUNE-Single Phase

The DUNE Far Detector has two LArTPC technologies, Horizontal Drift (HD) and Vertical Drift (VD), as mentioned in Chapter 2. ProtoDUNE-SP was DUNE’s first full-scale Single-Phase prototype detector, which models a smaller version of the FD1-HD (see Section 2.5.1), and was a crucial part of DUNE’s effort toward the construction of the first DUNE 10-kt fiducial mass Far Detector module. Even as a prototype, the ProtoDUNE-SP experiment is the largest monolithic Single-Phase LArTPC detector built to date, with a total liquid argon (LAr) mass of 0.77 kt. It is housed in an extension to the EHN1 hall in NP04 [26], assembled and tested at the CERN Neutrino Platform [64]. The CERN Neutrino Platform constructed a test beam that delivered charged pions, kaons, protons, muons and electrons with momenta in the range 0.3 GeV/c - 7 GeV/c.

ProtoDUNE-SP prototypes the designs of most of the Single-Phase DUNE Far Detector module (FD1-HD) components at a 1:1 scale, with an extrapolation of about 1:20 in total LAr mass. As mentioned in Chapter 2, the inner detector elements, the time-projection chamber (TPC), the cold electronics (CE), and the Photon Detection System (PDS), are immersed in a cryostat filled with LAr. The TPC and CE are needed for event reconstruction and is used to measure cross sections of interactions of charged particles in LAr. The PDS is needed for non-beam event timing, such as atmospheric neutrinos, proton decay, and SN detection. The PDS also provides prompt signal, t0, for μs event time determination, which will improve the TPC’s spatial localization along drift direction, enable accurate ionization-signal-attenuation, and can potentially provide calorimetry. ProtoDUNE-SP’s large active volume allows for good containment of the hadronic and electromagnetic interaction products in the few GeV range, while the LArTPC features precise 3D tracking and accurate measurement of energy deposited. This combination is a first of its kind in one detector. Beam measurements also provide a calibration data set for tuning Monte Carlo
simulations and a reference data set for the DUNE experiment. Our first performance results have been published [44] and are discussed in detail in the next chapter. Further, ProtoDUNE-SP has been key in validating a full-scale DUNE detector technology and engineering components, continuing to demonstrate it’s long term operational stability of all detector components. The technical components of the experiment will be discussed in this chapter, and detailed further in our technical paper [26].

5.1 Experimental Goals

ProtoDUNE-SP uses many of the full-scale components the DUNE FD1-HD plans to use. However, it being a prototype, ProtoDUNE-SP uses 6 APAs instead of 150, and two drift volumes instead of four. An overview of ProtoDUNE-SP’s Time Projection Chamber (TPC) is shown in Figure 5.1. In addition, the reduced detector (relative to a Far Detector module) also reduces the requirements on the data acquisition, the amount of liquid argon, diagnostic subdetectors and many other detector-related systems, like the Photon Detection System (PDS).

ProtoDUNE-SP tests for the internal electronics, both those handling beam particle signals (charge + light) and those meant for diagnostics. One core principle of the planned DUNE Far Detector is the electron drift length of a 3.6 m, which corresponds to the distance between the cathode and anode planes in the TPC. Anode Plane Assemblies (APAs) are the most important building blocks of the DUNE FD1-HD (see Section 2.5.1)—they detect ionisation electrons liberated within the detector and measure their properties, such as total charge, position and time of arrival. Their wire planes are complex, which requires understanding the proper fabrication, as it is difficult to modify.

Another major goal of ProtoDUNE-SP was determining the optimal light detection technology for scintillation detection. ProtoDUNE-SP allowed us to use a charged particle beam of known composition and momentum, measuring the light response using three independent photon detector
Figure 5.1: This figure shows a schematic depiction of the major components of the ProtoDUNE-SP Detector [25].

DUNE’s FD1-HD will have 150 APAs per module, totalling 600 for the $4 \times 10$kt FD1-HD modules. Each APA can integrate 10 PDS modules per APA. Therefore, ProtoDUNE-SP was essential for full-scale testing APAs and determining which PDS detector technology is optimal is vital to understand before production of the DUNE Far Detector.

5.2 ProtoDUNE-SP Detector

The ProtoDUNE-SP detector is designed with a close to cube-like geometry, with dimensions of 7.2 m along the drift direction (x coordinate), 6 m in height (y coordinate) and 7 m following the
Figure 5.2: This figure shows a visual of the ProtoDUNE-SP detector. X-coordinate: the drift direction. Y-coordinate: height of detector. Z-coordinate: following the particle beam. Therefore, displaying the beam-pipe coming from the upstream (-Z) into the detector [30].

charged particle beam (π, p, e) direction (z coordinate), as shown in Figure 5.2. The full detector is suspended through the Detector Support Structure (DSS) from the cryostat roof and submerged in the LAr. Table 5.1 gives an overview of the key design and operation parameters of ProtoDUNE-SP. ProtoDUNE-SP consists of two drift volumes separated by the Cathode Plane Assemblies (CPAs) which are located in the middle of the detector spanning the y - z plane. The ionisation charge produced in the drift volume by the charged beam particles is drifted to the wire plane readout and projections of said particle tracks are recorded on the wires as electric signals. The CPA carries the high voltage (HV) that provides the necessary electric field of 500 V/cm in order to properly drift the electrons to the APA wires.

5.2.1 Test Beam

ProtoDUNE-SP received a charged particle beam from the Super Proton Synchrotron (SPS). The aim of this beam was to simulate as accurately as possible the particles resulting from a neutrino interaction in the eventual DUNE Far Detector. As discussed in Section 2.5.1, DUNE’s FD1-HD expects a neutrino beam in the GeV range, which matches nicely with ProtoDUNE-SP’s beam.
Figure 5.3: A schematic diagram showing the relative positions of the trigger counters (XBTFs), bending magnets (triangles), profile monitors (XBPFs) and Cherenkov detectors (XCETs) in the H4-VLE beam line. Combining data from different pieces of instrumentation can be used for triggering, reconstructing momentum and measuring time of flight [26].

The 400 GeV/c primary proton beam is extracted from the (SPS) and is directed towards a beryllium target, which produces a mixed hadron beam with a momentum of 80 GeV/c. This secondary beam is then propagated to impinge on a secondary target, producing a very low energy (VLE) tertiary beam in the 0.3 - 7 GeV/c momentum range. The H4-VLE beam line then transports these particles to the ProtoDUNE-SP detector. The secondary target material can be changed between copper and tungsten. The latter is chosen for momenta below 4 GeV/c in order to increase the hadron content of the beam. However, during operations the copper target was unintentionally used for the 2 GeV/c run instead of the tungsten target.

The H4-VLE beam line is instrumented with three types of detectors that provide particle identification and a trigger for the TPC. There are eight profile monitors (“XBPF”), three trigger counters (“XBTF”) and two threshold Cherenkov counters (“XCET”). In addition, there are three bending magnets that direct the beam toward the ProtoDUNE-SP detector. The second of these magnets is also used as part of a momentum spectrometer. The relative positions of each of these
features can be seen in Figure 5.3. For a detailed description of the beam line design, please reference here [65].

The XBPFs are placed at several points along the beam line. This arrangement allows the beam position to be tracked on a particle-by-particle basis and for the data to be used in the reconstruction of a particle’s momentum. Hits in the last two sets of XBPF devices are used to measure the trajectories of the beam particles that are then extrapolated to the face of the ProtoDUNE-SP TPC described in detail in [66]. The XBTFs are designed in a similar way; the signals from upstream and downstream planes, which are separated by 28.575 m, are connected to a time-to-digital converter (FMC-TDC [67]). The TDC signals from these two planes provide a particle’s time of flight (TOF), with resolution approximately 900 ps [68].

Coincident signals from the middle and downstream XBTFs act as a “general trigger.” During data taking across the momentum range, the measured efficiencies of the XBPFs with respect to these triggers are greater than 95% for all chambers [68]. The two Cherenkov counters used in the H4-VLE are of similar design [69, 70], although one is able to sustain a higher radiator gas pressure. The internal pressures of the two devices were tuned to tag different particle species at various momenta. Combining the TOF and the two Cherenkov signals (high and low pressure) allows us to determine the PID for analysis across the whole momentum spectrum of interest. During the beam run, signals from these devices were sent to the Central Trigger Board (CTB) to form High-Level Triggers (HLTs) tagged as various beam particle species, providing particle identification (PID) for the various particle types ($p$, $\mu$, $\pi$, $e$, $K$).

### 5.2.2 Cosmic Ray Tagger

The Cosmic Ray Tagger (CRT) is a system of scintillation counters that covers almost the entire upstream and downstream faces of the TPC. It was installed in order to provide triggers to read out the detector for a set of cosmic ray muons that pass through with known timing and direction,
more-or-less parallel to the TPC readout planes. Since the ProtoDUNE-SP detector is on the surface, it is never quiet, and is exposed to 20 kHz of cosmic ray muons. Most of these muons are not tagged before entry into the TPC. Both tagged and untagged muons provide important calibration data and performance indicators.

The scintillation counters used in the CRT were originally built and deployed for the outer veto of the Double Chooz experiment [71]. The CRT is composed of 32 modules, each of active area $1.6 \, \text{m} \times 3.2 \, \text{m}$, arranged into mechanically independent super-modules of four modules each. A schematic of a CRT module is shown in Figure 5.4. Each module is instrumented with 64 scintillator strips 5 cm wide and 365 cm long, arranged in two parallel planes of 32 each.

Figure 5.4: Drawing of the downstream CRT module assembly, showing the four super-modules positioned in a square. Each super-module consists of two modules edge-to-edge with scintillator strips running in the $x$ direction, and either behind or in front of them, two modules with strips running in the $y$ direction. For the upstream portion, the assembly is split in two, left and right, as shown in Figure 5.2 [26].
Each strip has a wavelength-shifting scintillating fiber that transports the light to an individual pixel of a 64 multi-anode photo-multiplier tube (Hamamatsu M64). The two layers of strips are offset by half a strip width to maximise coverage. The extra centimeters of strip, compared to the length of a module (320 cm), are outside the active area. Each module measures a one-dimensional spatial position from its strip number and measures its given position along the \( z \)-direction from its super-module’s placement. To reconstruct a CRT hit in three-dimensions, two modules are placed edge-to-edge with their strips all parallel, and two more placed behind them in the \( z \)-direction with their strips rotated by 90 degrees. This produces one super-module of dimensions 3.65 m by 3.65 m, as illustrated in Figure 5.4.

For the ProtoDUNE-SP downstream face, four super-modules are arranged edge-to-edge in a square roughly the size of a ProtoDUNE-SP face, also shown in Figure 5.4. This assembly of CRT modules is centred with respect to the centre of the TPC in the \( x \)-direction and placed 10.5 m from the upstream face of the TPC in the cryostat. The positioning of the upstream super-modules of the CRT system is complicated by the presence of the beampipe requiring that this portion of the CRT system be split, with the right and left halves offset from each other in the \( z \)-direction. One set of the two vertically stacked super-modules is placed 2.5 m from the front face of TPC (left of beam) and the other (right of beam) is placed 9.5 m upstream of it, which is shown in Figure 5.2 when looking carefully. In each stack, the upper and lower super-modules are actually offset slightly from each other in the \( z \)-direction (the upstream to downstream direction) so that they can both hang from the same bar.

### 5.2.3 Cryostat

The ProtoDUNE-SP cryostat is a free-standing steel-framed vessel with an insulated double membrane, based on the technology used for liquefied natural gas (LNG) storage and transport. The detector elements, consisting of the time projection chamber (TPC), the cold electronics (CE),
and the Photon Detection System (PDS), are housed in a cryostat that contains the LAr target material. The cryostat, a free-standing steel-framed vessel with an insulated double membrane, is based on the technology used for liquefied natural gas (LNG) storage and transport.

A cryogenics system, not so different that the Blanche and TallBo experiments discussed in Chapter 4, maintains the LAr at a stable temperature of about 89 K and at the required purity level through a closed-loop process that recovers the evaporated argon, recondenses and filters it, and returns it to the cryostat. The argon purification system is the largest constructed to date, as compared to previous devices, such as ICARUS [51], ArgoNeuT [72], LongBo [73], MicroBooNE [42], and the 35-ton prototype [74].

5.2.4 TPC

The ProtoDUNE-SP TPC encompasses two drift volumes, composed of six APAs are arranged into two APA planes, each consisting of three side-by-side APAs. Between them, a central cathode plane, composed of 18 CPA modules, splits the TPC volume into two electron-drift regions, one on each side of the cathode plane. A cartoon of this is shown in Figure ??, where the left figure is showing the x-z plane (bird’s-eye view) and the right side showing the (drift facing) x-y plane. The detector is sealed in the y-x plane by the End Walls of the Field Cage. The top and bottom are sealed by the Top and Bottom Field Cages (FCs). Each TPC drift field structure composed of FC, APAs, & CPAs acts like a Faraday cage to maintain a homogeneous electric field within each drift volume, including shielding it from either TPC volume and nearby cryostat. One drift region from ProtoDUNE-SP is shown in Figure 5.6. After the cryostat is filled to a height of about 7.3 m (pressure maintained ∼ 1050 mbar), the CPA is biased at a high potential of -180 kV to achieve the nominal 500V/cm drift field. A single drift region from ProtoDUNE-SP is shown in Figure 5.6.

The cathode plane is an array of 18 (six wide by three high) CPA modules, which consist of flame-retardant FR4 frames, each 1.18 m wide and 2 m high, that hold thin panels with a resistive
Table 5.1: Nominal LArTPC parameters and features. Here, X refers to all collection planes, and Z and C refer to the collection planes on the sides of the TPC and cryostat, respectively [44].

<table>
<thead>
<tr>
<th>TPC configuration</th>
<th>Anode-Cathode-Anode (2 active volumes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC dimensions (active volumes)</td>
<td>6.086 (h) × 3.597 (w) × 7.045 (l) m³</td>
</tr>
<tr>
<td>(instrumented volumes)</td>
<td>5.984 (h) × 3.597 (w) × 6.944 (l) m³</td>
</tr>
<tr>
<td>Total active volume (nominal, at room T)</td>
<td>2 × 154 m³</td>
</tr>
<tr>
<td>Total instrumented LAr mass (87.65 K)</td>
<td>419 t</td>
</tr>
<tr>
<td>Number of TPC wire planes</td>
<td>4 (G, U, V, X)</td>
</tr>
<tr>
<td>Number of wires (total)</td>
<td>15360 (instrumented)</td>
</tr>
<tr>
<td></td>
<td>2 × 2880 (non-instrumented)</td>
</tr>
<tr>
<td>G: Grid plane</td>
<td>2 × 2400 (instrumented, wrapped)</td>
</tr>
<tr>
<td>U: 1st induction plane</td>
<td>2 × 2400 (instrumented, wrapped)</td>
</tr>
<tr>
<td>V: 2nd induction plane</td>
<td>2 × 1440 (instrumented)</td>
</tr>
<tr>
<td>Z: TPC-side collection plane</td>
<td>2 × 1440 (instrumented)</td>
</tr>
<tr>
<td>C: Cryostat-side collection plane</td>
<td></td>
</tr>
<tr>
<td>Wire orientation (w.r.t. vertical)</td>
<td>G: 0°, U: +35.7°, V: −35.7°, X: 0°</td>
</tr>
<tr>
<td>Wire pitch (normal to wire direction)</td>
<td>4.79 mm (G, X); 4.67 mm (U, V)</td>
</tr>
<tr>
<td>Wire type</td>
<td>Cu-Be Alloy #25, diam. 150 µm</td>
</tr>
<tr>
<td>Gap width between planes</td>
<td>4.75 mm</td>
</tr>
<tr>
<td>E-Field (nominal) in drift volume</td>
<td>500 V/cm</td>
</tr>
<tr>
<td>Cathode plane voltage</td>
<td>−180 kV</td>
</tr>
<tr>
<td>Anode plane bias voltages</td>
<td>G: -665 V, U: -370 V, V: 0 V, X: +820 V</td>
</tr>
<tr>
<td>Ground mesh</td>
<td>0 V</td>
</tr>
<tr>
<td>Max. drift length</td>
<td>2*3572 mm</td>
</tr>
<tr>
<td>(Cathode-to-G-plane distance at 87.65 K)</td>
<td></td>
</tr>
<tr>
<td>Drift velocity (nominal field, 87.65 K)</td>
<td>1.59 mm/µs</td>
</tr>
<tr>
<td>Max. drift time (nominal field, 87.65 K)</td>
<td>2.25 ms</td>
</tr>
</tbody>
</table>
Figure 5.5: This figure shows a schematic depiction of two sets of APA & CPA planes that split the ProtoDUNE-SP detector into two TPC electron-drift regions, one on each side of the cathode plane. Left: showing the x-z plane (bird’s-eye view). Right: showing the (drift facing) x-y plane. 

coating on both sides. Each anode plane is constructed of three adjacent Anode Plane Assemblies (APAs) that are each 6 m high by 2.3 m wide in the installed position. Each APA consists of a frame that holds three parallel planes of sense and shielding wires on each of its two faces; the wires of each plane are oriented at different angles with respect to those making up the other planes to enable 3D reconstruction, as discussed in Section 3.2.1.

Signals from the wires of each APA are read out via Cold Electronics (CEs), which are mounted onto the APA frame and thus, immersed in LAr. Each APA is read out by 20 front-end motherboards (FEMBs), that amplify, shape, and continuously digitize the U, V, and X signals on the sense wires at several MHz. A total of 2,560 electronics channels transmits these waveforms to the Data Acquisition system (DAQ).

The coordinate system is such that the z coordinate points in the direction of the beam that enters through the Beam Plug (BP), shown on the left side of the detector in Figure 5.1. The
Figure 5.6: This figure shows a single ProtoDUNE-SP TPC volume drift region. An APA plane, shown on the left, a CPA plane, shown on the right, and a field cage (FC), which is completely surrounding the four open sides of the drift region- this ensures that the electric field within is uniform and unaffected by the presence of the cryostat walls and other nearby conductive structures. The coordinate origin is fixed to the bottom point where the CPA starts. Therefore, the x coordinate is pointing in the drift direction, the drift volume that receives the beam is associated with the negative x coordinate component and is usually called the beam right side, as it extends to the right if one is looking in the beam direction. The other drift volume is referred to as the beam left side.

5.2.5 Photon Detection System

Each APA contains ten photon detector modules, shaped as long, thin bars oriented horizontally (\( \hat{z} \) direction) perpendicular to the \( \hat{x} \) drift direction behind the wire planes. Figures 5.5 & 5.6
Figure 5.7: This figure shows a ProtoDUNE-SP APA with all (3) type of PDS technologies. Each photon detector module is shaped as long, thin bars oriented in parallel to an APA (\(\hat{z}\) direction) and perpendicular to the electron drift (\(\hat{x}\) direction); behind the wire planes at a distance of \(\sim 60\) cm from one another in the \(\hat{y}\) vertical dimension. The 3 designs are listed from top-bottom and shown left-right, respectively, with the center module being developed by IU (Double-Shift Lightguide).

show where and how the PDS modules were installed. Of the sixty photon detector modules that were installed in ProtoDUNE-SP, three technologies were implemented in the experiment: twenty nine "Double-Shift Lightguide" modules, twenty nine "Dip-Coated Lightguide" modules, and two "ARAPUCA" modules. All lightguide modules have the same installation dimensions (207.4 \(\times\) 8.2 cm\(^2\) optical area) and single-side read-out at one end of the bar. The ARAPUCA modules are segmented longitudinally (along \(z\) direction) in 12 cells with independent read-out, 8 with 9.8 \(\times\) 7.9 cm\(^2\) optical area and 4 with double area (19.6\(\times\)7.9 cm\(^2\)).
As the Photon Detectors are key to my thesis, the next section will go over the conceptual design behind all three PDS technologies that were implemented into ProtoDUNE-SP. One example of each module type is highlighted in Figure 5.7. Furthermore, Chapter 6 will go into depth about the PDS installation, commissioning, & operations.

5.3 Photon Detector Technologies Designs

The following sections will describe three conceptual PDS designs for the DUNE FD1-HD PDS, which are referred to as Dip-Coated Lightguides, Double-Shift Lightguides, and the ARAPUCA modules. As discussed in Chapter 2, the DUNE-SP concept involves large volumes, with APAs being fully submerged within the LAr. Previous approaches have been relatively small volume detectors, like ICARUS T600 and MicroBooNE [75, 76]. In addition, there are three main constraints that must be requisite for an adequate PDS for FD1-HD: (1) the PDS must be sensitive to low levels of light (0.5 photo-electron/MeV of energy deposition) and have a minimum 100 ns timing resolution (2) It must not interfere with the operation of the TPC (3) must be implemented so as to minimize cost, while maximizing light detection efficiency. In each technology, incident LAr scintillation photons (see Section 3.2.2) are converted into longer-wavelength photons using photofluorescent compounds as wavelength shifters (WLS). Visible light is trapped within the modules, a portion of which is eventually incident on an array of silicon photomultiplier photosensors.

Before implementing into ProtoDUNE-SP, thorough tests were made for all three technologies, using the Blanche & TallBo dewars at PAB, Fermilab (see Sections 4.3 & 4.4).

5.3.1 Dip-Coated Lightguide Technology

The Dip-Coated Lightguide design is a very simple technology, efficient, and very inexpensive. It allows for easy handling and assembly, and most importantly, requires less space than traditional UV photosensors, such as photomultiplier tubes (PMTs) arrays, which were implemented the ICARUS
Figure 5.8: This figure shows the Dip-Coated Lightguide design. As shown, the VUV 128 nm scintillation light strikes a TPB surface-embedded UVT acrylic lightguide. This TPB wavelength shifts the VUV light to the visible-blue (420-450 nm) and is then guided, via total internal reflection, down to one end where they are read out by a photosensor array.

The Dip-Coated Lightguide technology was developed by MIT and Fermilab [77] and is constructed as a bar, coated with tetraphenyl-butadiene (TPB), as shown in Figure 5.8. The lightguide technology converts the 128 nm LAr scintillation light to the visible light, which is guided to one end, via total internal reflection, and read out by an array of silicon photomultipliers (SiPMs).

The lightguide is made of cast UTRAN UV-transmitting acrylic, with an index of refraction of 1.49 [77]. As these are commercially manufactured, they are then cut into bars (of appropriate length) and diamond polished on all surfaces. Further, in order to reduce the amount of crazing, the bars are then annealed before coating with TPB. The bars are annealed using by warming the bar to 230 degrees Fahrenheit for 3 hours. The temperature is then stepped down to 120 degrees, by 10 degree increments, and are then removed and is allowed to cool for 30 minutes. The bars are then wiped down with pure ethanol [78]. Following the annealing procedure, a specialized mechanized system dips the bars into a TPB solution, composed of: 50 ml toluene and 12 ml ethanol, which 0.1 g acrylic beads are dissolved for every 0.1 g TPB. The coating is applied directly to the bar via this dipping procedure, enabling TPB acrylic matrix to directly embed into the bar [77, 79].

The TPB coating efficiently absorbs the VUV light and reemits visible-blue photons, typically ranging from 420-450 nm [57]. The converted photons are then guided via total internal reflection
Figure 5.9: This cartoon shows the Double-Shift Lightguide design. This technology was originally designed similar to the Dip-Coated Lightguide technology, however, has evolved to enhance reproducibility, as well as separating the conversion from UV light to visible wavelengths. As shown in the figure, the VUV 128 nm scintillation light strikes a TPB surface-embedded acrylic plate and converts the VUV light to the visible-blue (420-450 nm). Once converted, the transmitted photons are subsequently absorbed by a commercial lightguide and are again wavelength shifted to the visible-green (480-510 nm). The light is then guided, via total internal reflection, down to one end where they are read out by a photosensor array.

down to one end where they are read out by a photosensor array.

5.3.2 Double-Shift Lightguide Technology

The Double-Shift Lightguide technology was developed by Stuart Mufson and our group at Indiana University [57]. This technology, originally designed similar to the Dip-Coated Lightguide technology, has evolved to enhance reproducibility, as well as separating the conversion from UV light to visible wavelengths [48]. As shown in Figure 5.9, the Double-Shift Lightguide is composed a commercial lightguide and a modified commercial acrylic radiator plate. The two separable WLS components allow for optimal performance and reproducibility, increasing efficiency of photosensor detection for light at 490 nm and deconvolves the wavelength shifting for production and quality control. Additionally, since the components of the Double-Shift Lightguides are separable, they can be independently studied and further optimized pre and post operation.
The outer WLS material consists of acrylic radiator plates that completely cover the lightguide (six on each side with respect to DUNE specifications), placed end-to-end. The plates are coated in a WLS solution consisting of 5 gm of scintillation grade (>99%) TPB to 1,000 gm of dichloromethane, using a Binks high-volume lower pressure sprayer system. Once the plates are coated, they are annealed in a vacuum oven at 80°C, a temperature just below the melting point of the acrylic plate. The annealing fuses the TPB into the acrylic, ensuring that it will not separate or precipitate due to aging or cryocycling in LAr.

The second WLS material and primary lightguide for the Double-Shift Lightguide technology is made from special commercial crosslinked polystyrene, EJ-280PSM, made by Eljen Technology. The polystyrene is cut into bars (of appropriate length) and both major faces clear as-cast and all edges diamond-milled. The advantages of using an unaltered lightguide, compared to the Dip-Coated Lightguide, are that uniformity across the bar is significantly enhanced, as well as reproducibility for all modules, allowing for a more uniform PD detector.

In summary, the VUV 128 nm scintillation light strikes a TPB surface-coated acrylic plate. The TPB coating efficiently absorbs the VUV light and reemits visible-blue photons, typically ranging from 420-450 nm. Once converted, many of the photons are subsequently absorbed by the EJ-280PSM commercial lightguide and are again wavelength shifted to the visible-green, typically ranging from 480-510 nm. Figure 5.10 shows the emission spectrum for the WLS radiator plates and the emission spectrum for the EJ-280PSM lightguide. The twice converted photons are then guided the same way as the Dip-Coated Lightguide, via total internal reflection, down to one end where they are read out by the same photosensor array readout used for the Dip-Coated Lightguides [57].

5.3.3 ARAPUCA Technology

The ARAPUCA concept was originally developed by Ana Machado and Ettore Segreto, both of the University of Campinas in Brazil. The ARAPUCA technology aims to enhance photon trapping
Figure 5.10: The left figure shows the emission spectrum for the TPB-coated radiator plates and the well-matched lightguide absorption spectrum. The right figure shows the emission spectrum for the EJ-280PSM lightguide and the photosensor (SiPM) PDE. This design allows for a moderate 128 nm photon detection efficiency, while deconvolving the 2-fold WLS components for production and quality control [57].

through the use of wavelength-shifting compounds and a commercial dichroic shortpass optical filter, all contained in a rectangular cell-like structure [80]. Typical cell dimensions are about 10 cm in width, 8 cm in length, and 2 cm in depth, as shown in Figure 5.11. Multiple cells are aligned end-to-end to form an ARAPUCA array module. The filter is created by using multi-layer thin films that are highly transparent to photons with a wavelength below a tunable cutoff and highly reflective to photons above this tunable cutoff.

The photon-trap process starts with the external face of the dichroic filter being coated with PTP, wavelength shifting the VUV 128 nm scintillation light to a range of 330-400 nm; 400 nm being the tuned cutoff. The transmitted photons pass through until they subsequently encounter a second (different) wavelength shifter, TPB, emitting photons in the 420-450 nm range. Figure 5.12 shows both TPB’s and PTP’s WLS emission spectra, with respect to the dichroic filter transmission and cutoff. All TPBconverted photons are then “trapped” within the region between the dichroic filter and the back-wall, whose internal surface is covered with an array of photosensors
Figure 5.11: This figure shows a schematic depiction of the ARAPUCA concept [63]. This design “traps” photons through the use of wavelength-shifting compounds and a commercial dichroic shortpass optical filter, all contained in a cell-like fashion. The left cartoon shows the individual components of the cell, while the right shows how the technology functions. As shown in Figure 5.12, this dichroic filter used with the two-fold WLS becomes highly transparent to photons with a wavelength below 400 nm and highly reflective to photons above 400nm, thus trapping the converted light within the region between the dichroic filter and the back-wall, whose internal surface is covered with photosensors and highly reflective acrylic foils [63].

and highly reflective acrylic foils, which are adhered to the back-end of the walls for maximum photon-reflectivity. Therefore, the twice converted light will be “trapped” in the ARAPUCA cell, reflecting back and forth until it is detected by the photosensors, as shown in Figure 5.11.
Figure 5.12: The transmission of the PTP WLS emission through the Dichroic filter is shown in the figure to the left. The TPB emission (second WLS) with the reflection spectrum of the dichroic filter is shown on the right. The average polarization is indicated in black, where each polarization is different due to the transmission and reflection of the dichroic filter. Given these spectra, reproduced by Totani et al. [63], the filter becomes highly transparent to photons with a wavelength below 400 nm and highly reflective to photons above 400nm, thus trapping the converted UV-light within the region between the dichroic filter and the back-wall, allowing for a photosensor readout [63].
Chapter 6

Constructing and Commissioning of the UV lens at ProtoDUNE-SP

A significant portion of my hardware and instrumentation experience was done during the production, installation/commissioning, and operations of the PD System for ProtoDUNE-SP. The following sections will begin with my work at Indiana University, specifically regarding the full-scale production process and quality control of the main components for the Double-Shift Lightguide modules in the ProtoDUNE-SP experiment. Continuing forward, the next sections will describe my work as the onsite subsystem lead for installing/commissioning and operations for the Photon Detection System for ProtoDUNE-SP. Once all modules were shipped to CERN they were inspected and tested for QA/QC.

After the installation process, I was responsible for integrating the PDS readout into the Detector Control System & Data Acquisition in order to fully commission the ProtoDUNE-SP detector. This included channel-by-channel inspection, testing, calibration, and full DAQ integration with the entire ProtoDUNE-SP system. Once the PDS was commissioned, I was responsible for onsite PDS operations during the entire test-beam runs, along with calibration runs. This included contributing to full beam shifts, online monitor support, and being the sole on-call PDS expert. This work allowed me to have a start-to-finish work for the core of my thesis and was vital for producing the necessary physics data needed for my main analysis, described in detail in Chapter 7.

ProtoDUNE-SP contains 6 Anode Plane Assemblies (APAs), each containing ten photon detector modules, shaped as long, thin bars oriented horizontally (z direction) perpendicular to the x drift direction behind the wire planes. Of the sixty photon detector modules, three technologies were implemented in the experiment: twenty nine ”Double-Shift Lightguide” modules, twenty nine are ”Dip-Coated Lightguide” modules, and two are ”ARAPUCA” modules. All lightguide modules have the same installation dimensions (207.4 × 8.2 cm² optical area) and single-side read-out at one
end of the bar. The ARAPUCA modules are segmented longitudinally (along z direction) in 12 cells with independent read-out, 8 with 9.8 × 7.9 cm² optical area and 4 with double area (19.6×7.9 cm²). One example of each module type is highlighted within an APA in Figure 5.7, the center one being developed by IU (Double-Shift Lightguides), described in detail in Section 5.3.2.

6.1 Double-Shift Lightguide Full-Scale Production at Indiana University

The Double-Shift Lightguide collector, as described in Section 5.3.2, combines the use of WLS TPB-coated radiator plates with a WLS lightguide bar. In this design, LAr scintillated light at 128 nm undergoes two wavelength-shifting steps, once to ∼430 nm blue light in the plate and then to 490 nm green light in the bar.

A conceptual example of the Double-Shift WLS lightguide is shown in Figure 5.9. The benefits of this design are in the increased efficiency of photosensor detection for light at ∼490 nm and in the production and quality control of the technology. During and after construction, bars are separable and components can be independently studied and optimized. Our group at Indiana University was solely responsible for producing the main components and quality control for the Double-Shift Lightguide modules in ProtoDUNE-SP.

6.1.1 Wavelength Shifting Acrylic Plates

The outer WLS material for a ProtoDUNE-SP Double-Shift module is composed of twelve separate radiator plates that completely cover the lightguide, six on each side, placed end-to-end. In total, our group produced 360 WLS plates + spares. Figure 5.9 shows a condensed version cartoon of this, only displaying once face with the acrylic plates. The acrylic plates were purchased from McMaster Carr (a trusted HEP industrial company) and were laser-cut in pairs at Fort Collins Plastics in Fort Collins, CO. These plates were required to meet the following dimensions within tolerances in order to be properly used for the Double-Shift Lightguide modules: (34.12 ± 0.10 cm) × (8.54 ±
for several years. He coats the plates using a standard that guides him to the correct coating thickness. This spraying technology would be commercialized so that the process would be uniform and the yield increased if this were the technology chosen.

The spraying process has been evaluated by Indiana University ES&H (report included in the readiness review package in docdb).

Figure 13. The fume hood at the Indiana University laboratory where the wavelength shifting plates are sprayed.

Once the plates are coated, they are baked overnight in a vacuum oven at 80°C. This temperature is just below the melting point of the acrylic. It allows the TPB to be incorporated into the plastic so that it does not flake off in the LAr.

At first the baking was done with a homemade oven constructed out of parts obtained from McMaster Carr. But this oven had a temperature gradient that is thought to be responsible for the plates shrinking, often by large amounts, during baking. Some plates suffered so much shrinkage that they no longer were able to meet the metrology requirements. Once the homemade oven was switched out with a commercial vacuum oven, the plates only rarely shrunk so much that they failed the metrology requirement.

Two plates are cut from a single piece of acrylic, along with three breakout tabs for quality control. The acrylic plates were then coated in a WLS solution consisting of 5 gm of scintillation grade (> 99%) of tetraphenyl-butadiene (TPB) to 1,000 gm of dichloromethane, using a Binks high-volume lower pressure sprayer system [57]. These plates were sprayed by hand by our IU technician (Brian Baugh). However, future procedure plans would industrialize this process, with the expectation of enhancement in WLS yield and uniformity. Therefore the acrylic plates and tabs are coated with the WLS at the same time (tab-plate-tab-plate-tab). Figure 6.1 shows the plates placed inside the fume hood (located at IU laboratory), where they were carefully coated with TPB infused WLS.

Once the plates were coated, they were annealed in a vacuum oven at 80°C, a temperature just below the melting point of the acrylic. The annealing incorporates the TPB into the acrylic, ensuring that it will not separate or precipitate due to aging or cryocycling in LAr. Metrology tests are carried out to ensure that no changes in the plate dimension occurred during annealing.

Figure 6.1: This figure shows the fume hood at Indiana University laboratory where the wavelength shifting acrylic plates carefully coated with TPB.
The quality of a wavelength shifting plate depends on (1) its brightness and (2) its metrology, that is, whether the radiator plate will fit into the photon detector frame.

1. Brightness

The brightness of a wavelength shifting plate is evaluated using a McPherson VUV monochromator with H$_2$ lamp source. The monochromator exposes the plate to 128 nm light. The plate converts the 128 nm light to the optical. The optical light is measured by a SensL SiPM. The evaluation is made using the two tabs on either side of the plate blank. The evaluation is relative in the sense that we accept plates for the IU PD technology if they are brighter than plates that are known meet the DUNE science goals.

To measure a plate in the VUV monochromator, its vacuum chamber is first filled with pure gaseous argon. Then the vacuum chamber is pumped down to purge residual N$_2$, O$_2$, and H$_2$O. Once the H$_2$ lamp is calibrated with a NIST-calibrated photodiode, measurements are made.

The WLS plates are then separated and the breakout tabs are tested for brightness using a McPherson VUV monochromator, containing a H$_2$ lamp source. Before measuring the plate, the VUV monochromator’s chamber is filled with gaseous argon. The vacuum chamber is then pumped down to purge any residual N$_2$, O$_2$, and H$_2$O. Measurements are then ready to begin once the H$_2$ lamp is calibrated, using a NIST-calibrated photodiode.

The VUV monochromator exposes the WLS plate to 128 nm light. The plate converts the 128 nm light to the optical and is measured by a SensL SiPM, as shown in Figure 6.2. Each plate is evaluated with respect to a standard tab, averaging the response from the two tabs on either side of it. The evaluation is relative; plates are accepted only if they are brighter than baseline plates that meet efficiency goals derived from DUNE physics requirements [57]. The measurement of baseline plate efficiency was conducted on a LAr test stand, discussed in Section 4.3. Batches of around 150 plates were measured at a time. Following these measurements, the WLS plates were then shipped as its own component, using a uniquely designed box that both protected the plates mechanically and protected against humidity, which has been shown to degraded the WLS material.
Figure 6.3: The figure shows the Double-Shift Lightguide, EJ-280PSM, special commercialized by Eljen Technologies. The material used in ProtoDUNE-SP is a special crosslinked polystyrene, and was casted to specific dimensions. The lightguides were cut into bars that were required to meet the following dimensions within tolerances: $(209.15 \pm 0.05 \text{ cm}) \times (8.6 \pm 0.05 \text{ cm}) \times (0.6 \pm 0.05 \text{ cm})$.

### 6.1.2 Wavelength Shifting Lightguides

The second WLS material and primary lightguide for the Double-Shift Lightguide is made from special commercial Eljen EJ-280PSM. Our group worked with the company Eljen Technologies in order to obtain the right commercial product. This company has a long history of producing quality products for high energy physics (HEP) experiments. The lightguide material used in ProtoDUNE-SP is a special crosslinked polystyrene, and was casted to specific dimensions to tolerances for insertion of an APA, shown in Figure 6.3. In total, our group tested 60+ lightguides and delivered our top 40, 30 + 10 spares.

Once the WLS lightguides were shipped to IU, two main criteria were tested: (1) metrology (2) attenuation length. The lightguides were cut into bars that were required to meet the following dimensions within tolerances: $(209.15 \pm 0.05 \text{ cm}) \times (8.6 \pm 0.05 \text{ cm}) \times (0.6 \pm 0.05 \text{ cm})$. The metrology was measured using a specialized metrology apparatus, design by Brice Adams (IU Electronic Instrumentation Engineer). These measurements were necessary to measure accurately, as there could be a mismatch in length when all components get to LAr temperature (87K), due to the $0.072 \text{ mm/C/m}$ coefficient of thermal expansion (CTE). During each measurement, as shown in Figure 6.4, multiple places were measured, including the temperature in the room. When comparing all the WLS lightguides, all were compared with measurements adjusted to length at $20^\circ C$. 

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Figure 6.4: The metrology was measured using a specialized metrology apparatus, design by Brice Adams. These measurements were necessary as there could be a mismatch in length, when all components get to LAr temperature (87K), due to the $0.072 \text{mm/}°\text{C/m}$ coefficient of thermal expansion (CTE). During each measurement, multiple places were measured, including the temperature in the room.

The second test done for the WLS lightguides to pass requirements was on the basis of internal attenuation length. This was measured at room temperature using a custom made darkbox, built by Brice Adams. This darkbox included a computer-controlled stepper motor, using LabVIEW software, which moved the 435 nm LED along the length of an Eljen lightguide. For each position, a few hundred pulse-signals are measure by arrays of SiPMs at both ends. In addition, an SiPM is placed on the other end of the lightguide—looking through the bar from LED to SiPM—to look for consistency in transmission as a measure of manufacturing uniformity. Figure 6.5 shows a cartoon of the darkbox setup. I developed an automation for both the LAbView scanning process and the offline analysis, in order take multiple scans per bar and to determine the attenuation length for all ProtoDUNE-SP lightguides measured at room temperature.

The correlation between attenuation length at room temperature and at LAr temperature was established at Indiana University on a set of shorter Eljen bars. The results of these combined
Figure 6.5: This figure shows a schematic depiction of the darkbox used for testing lightguides, which included a computer-controlled stepper motor, using LabVIEW software, which moved a 435 nm LED along the length of an Eljen lightguide. For each position, a few hundred pulse-signals are measure by arrays of SiPMs at both ends, in order to determine the attenuation length.

studies showed that a room temperature attenuation length measurement greater than 6.4 m in the dark box ensured an attenuation length in LAr greater than 2 m [81]. An attenuation length greater than 6.80 m as measured in the dark box at Indiana University was therefore required for acceptance, since the attenuation length should be greater than the length of the lightguide.

Figure 6.6 shows an example attenuation length and transmission measurement using the darkbox scanner, where the two measurements were made from either side of the lightguide.

The WLS lightguides used for ProtoDUNE-SP arrived in one batch from the manufacturer. All lightguides were tested using the 2 criteria explained above, and the best 40 lightguides were then shipped for assembly. The WLS lightguides were more robust than the WLS acrylic plates, so a standard shipping method was used.
Figure 4: Analysis of the dark box measurements of Eljen light guide #20. The upper panel of Fig. 4 shows that the attenuation length as measured at both ends is long and both ends give consistent results. In addition, the transmission measurements show no evidence for irregularities in the manufacture.

Measurements for all 40 Eljen light guides in the dark box are given in Table 1 below. As described in the next section, attenuation lengths > 6.25 m in the dark box are correlated with attenuation lengths longer than 2m in LAr. If the attenuation length in the dark box is < 6.25 m, the light guide was rejected. Of the 40 light guides purchased from Eljen, 25 were accepted and 15 were rejected based on our criteria.

Figure 6.6: This figure shows an example attenuation length and transmission measurement using the darkbox scanner, where the two measurements were made from either side of the lightguide.

6.2 ProtoDUNE-SP PDS Installation at CERN

The advantage of having multiple collaborators (see Section 5.7) for the production of each design allowed there to be spare modules shipped to CERN. All fabricated components for each of the three PDS designs were shipped to CSU for full detector assembly. Once assembled, a module would undergo rigorous tests, such as photon collection performance and post-thermal cycling functionality. The highest quality modules were then shipped to CERN.

Therefore, all PD modules for ProtoDUNE-SP arrived at CERN ready for installation. The PD modules shipped from Colorado State University (CSU) contained 12 PD modules individually packaged in an anti-static bag and placed between anti-static foam. Upon receiving the modules, quality control inspections were made to verify the module components were not damaged and still performed as expected. This included a visual inspection of each PD module and a pseudo-attenuation length measurement of each module.

Once the PDs were installed into an APA, the entire APA and its components were tested in the Cold Box, using gaseous argon[44]. The full PDS chain, including photosensors, cold cables, warm cables, SSP, DAQ, and the connection to the slow control system was then tested. This included each PDS channel being tested and thermal-cycled at ∼ 150K.
Figure 6.7: This figure shows the darkbox used in the clean room at CERN, as well as how we inserted a completed module for testing. We used a software called LBNEWare as the DAQ, which interfaced with a LabVIEW controlled stepper-motor for testing.

Each PDS channel was tested for functionality, stability, trigger rates, threshold calibrations, and PD module response and comparison. With respect to the slow control and DAQ, nominal configuration settings were implemented in GUI format, with additional upload-able configurations. Data rates were also tested in order to maximize data taking to the Detector Control System’s data limits.

The Cold Box data allowed the preparation for online monitoring diagnostics, which helped determine if live data was sufficient or not. Diagnostics monitoring included things such as persistent traces, leading-edge amplitude histograms, integral waveforms, average waveforms, internal/external triggering, for every PDS channel. Figure 6.16 shows an example of how four channels were verified in functionality an response, via persistence traces, using the online monitor system.

Following the cold box tests and final QA/QC, the PDS was moved to its final destination, the cryostat. Once installed into the cryostat, final cable/channel/visual checks were made before commissioning the PDS detector into the ProtoDUNE-SP system.
Figure 6.8: This figure shows a PDS module scanned in the darkbox at CERN. The left figure shows an individual scan distribution, pulsing an LED 5,000 at a single position. The right figure shows the mean response along the PD module for a complete scan.

6.2.1 ProtoDUNE-SP PDS Q/A & Q/C

At CERN we used a darkbox similar to the one used at IU (figure 6.5) to scan each completed PD module. We used a software called LBNEWare as the DAQ, which interfaced with a LabVIEW controlled stepper-motor for testing. Figure 6.7 shows the darkbox used in the NP04 clean room at CERN, as well as how we inserted a completed module for testing.

The standard procedure for the PDS darkbox scanning measurements started with the photosensors (SiPMs/MPPCs) and the darkbox-LED being allowed to warm up for 30 minutes, at nominal voltages. This assured stability within each scan and reliability for module-to-module comparisons. For each module scan, the LED was set to pulse and read out 5000 times per location, at multiple locations, along each side of the PD module. This allowed for sufficient signal observation and determination of the mean response of the module along each position. An example signal distribution and a finished scan along a module in shown in Figure 6.8. The mean response was determined by fitting a Gaussian to the 5000 integrated waveforms.

Since these scans were looking at an entire assembled module, versus just the WLS lightguides
discussed in Section 6.1.2, a pseudoadtenuation was measured. Prior to arrival at CERN, a pseudoadtenuation length had been calculated for each PD module using the relative brightness (mean signal) along each position. Once at CERN, a pseudoadtenuation length was measured to cross-check the modules response with its original measurement made before traveling. In addition, these ready-to-install modules were measured on both faces of the individual module, labelled Side-A & Side-B. Finally, once all modules were scanned and reviewed, the best pseudoadtenuation length was confirmed for installation into the APA, placing the best module-side facing the TPC for the best photon yield response.

### 6.2.2 Photon Detector APA Installation

Each APA frame holds ten PDS modules, via internal rails, equally spaced along the full vertical length of the APA frame. The spacing between modules along the $y$ direction was approximately 60 cm. PDS modules were inserted into the frames of completed APAs, between the sets of wire layers. This installation process was very delicate procedure, as mishandling a module could result in degradation, channel disconnection, or module/APA failure. Therefore, a procedure was developed and followed to ensure proper handling of PD modules, while inserting them into an APA.
### PD Channel Mapping

<table>
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<tr>
<th>Module ID</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Channel #</th>
<th>Channel Info</th>
<th>PD Module HB</th>
<th>SSP Serial #</th>
<th>SSP IP #</th>
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<tr>
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<td>Hamamatsu</td>
<td>SSP503</td>
<td>2</td>
<td>216-219</td>
<td>35</td>
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<td>220-223</td>
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</tr>
<tr>
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<td></td>
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<td>003-0026-07</td>
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<td>SSP501</td>
<td>0</td>
<td>192-195</td>
<td>23</td>
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<td></td>
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<tr>
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<td>SSP504</td>
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<td>232-235</td>
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<td>28</td>
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</tr>
</tbody>
</table>

### Figure 6.10

This figure shows a complete detailed channel mapping of all PDS channels, photosensor information, and physical location of connecting components.

### Figure 6.9

Figure 6.9 shows how we installed a PD module using a special installation rail and a lift (left figure), as well as the completion of 30 modules installed in 3 APAs within the cryostat (right figure).

For each APA, cryogenic PD cables were installed at the same time as the PD modules. Each APA has 10 Cat6 PD cables, one per module, with alternating installation sides (shown in Figure 6.11). For each five cables per side of each APA, the cables were routed up through a hollow inner-channel to the top of the APA. Therefore, PD cable installation, for either the coldbox or cryostat, were routed straight to a flange feedthrough. From there, warm Cat6 cables were connected to the SSP modules (described in Section 4.1.2). Each APA had a four corresponding SSPs, further shown in Figure 6.12.

In total, 29 Double-Shift Lightguides, 29 Dip-Coated Lightguides, and 2 ARAPUCA devices were installed into ProtoDUNE-SP. For a fair technology comparison, the Double-Shift and Dip-Coated Lightguides alternated vertically along an APA. For the two ARAPUCA modules, one in placed in APA 3, directly in front of the beam plug for the observation of photons from beam interactions, and the other in the middle of APA 6 to observe photons from cosmic particles.
Figure 6.11: SSP Setup and Readout GUI in the DCS. All channels for all SSPs can be biased and readout from the DCS software.

Figure 6.12: PDS Cable Routing. From left to right, the three pictures show cold cables connecting to the flange from inside the cryostat, warm cables connecting from the warm side of the flange, and warm cables connecting from the flange warm side to the SSPs.
Figure 6.13: This figure shows the complete physical PD module and PDS channel mapping for the detector. Including all component type and integration connections in detail.

Figure 6.10 explains the physical mapping from APA frame to PD module, including the alternating installation (insert) side. A complete detailed channel mapping of all PDS channels, photosensor information, and physical location of connecting components are explicitly shown in Figure 6.13.

### 6.2.3 Photon Detector Calibration and Monitoring System

A pulsed UV-light monitoring and calibration system, designed and fabricated by Argonne National Laboratory, was installed to measure the photon detector gain, linearity, and timing resolution, and to monitor stability and the system response over time. Figure 6.14 shows a schematic of the ProtoDUNE-SP Photon Detector Calibration and Monitoring (DCM) system. The system hardware consists of both warm and cold components. Diffusers mounted on the cathode plane assembly panels serve as a light sources that uniformly illuminate the APA face containing the PDS modules.
Figure 6.14: This figure shows a schematic of the ProtoDUNE-SP Photon Detector Calibration and Monitoring (DCM) system. Diffusers mounted on the cathode plane assembly panels serve as a light sources that uniformly illuminate the APA face containing the PDS modules.

The system has no active components within the cryostat. The active system component consists of a 1U rack mount Light Calibration Module (LCM) sitting outside the cryostat. The LCM generates light pulses that propagate through a quartz fiber-optic cable to diffusers at the CPA. Calibration module consists of a FPGA-based control logic unit coupled to an internal LED Pulser Module (LPM) and an additional bulk power supply. The LPM utilizes multiple digital outputs from the control board to control the pulse characteristics. The light pulses are triggerable, where triggers come from either a periodic internal trigger, or from an external trigger from the timing system, with respect to the trigger and timing system.

The DCM system produced UV light flashes with predefined pulse amplitude, pulse width, repetition rate, and pulse duration. Figure 6.15 shows an example of the PDS DCM flashing a PDS module with predefined pulse amplitude and pulse width. Pulse multiplicity control also offers a possibility to produce two pulses at fixed time difference to study timing properties of the photon system, which will be discussed in a future analysis Section 7.5.4.
Figure 6.15: This figure shows an example persistence trace, where the PDS DCM flashes a PDS module, with predefined pulse amplitude and pulse width.

6.2.4 Coldbox tests at CERN

Once the modules were fully installed into an APA, the APA and the PDS modules were tested in the NP04 coldbox, using gaseous Argon. Since the coldbox is essentially a darkbox, we used a simplified version of the PDS calibration system to flash each module, discussed above (Section 6.2.3). This allowed for a deeper channel inspection, preliminary calibrations (knowingly at different temperature), and relative module performance. This included each PDS channel being tested for functionality, stability, trigger rates, threshold calibrations, and PD module response and comparison. With respect to the Detector Control System (DCS) and DAQ, nominal configuration settings were implemented in GUI format, with additional upload-able configurations. Data rates were also tested, using the DCMs, in order to maximize data taking to the DAQ’s data-limits.

During the cold box tests, the PDS was fully interfaced with both the DCS and the monitoring system. Photosensors were biased and unbiased from the DCS, their status were displayed, and the bias voltage was modified manually or according to different preset conditions, as shown in Figure 6.20.
Figure 6.16: This figure shows example persistent waveforms of four PDS channels tested in the Coldbox. Each plot shows the raw response of the photon detector channel under quality control testing in the CERN coldbox before installation into ProtoDUNE-SP.

The Cold Box data allowed the preparation for online monitoring diagnostics, which helped determine if live data was sufficient or not. Diagnostics monitoring included things such as persistent traces, leading-edge amplitude histograms, integral waveforms, average waveforms, internal/external triggering, for every PDS channel. Figure 6.16 shows an example of how four channels were verified in functionality and response, via persistent traces, using the online monitor system. Data rates were also tested using the DCMs and the DAQ data limits were established and optimised for data taking.

The coldbox tests allowed for a deeper channel inspection, preliminary calibrations, and relative module performance. It also provided an opportunity to observe faults with the grounding or disconnects in the SSPs, channels, and cables. If one module deemed inadequate, we could easily replace said module before entering the cryostat- fortunately, this was only done for one module.
Following the cold box tests and final QA/QC (for both PDS and APAs), the PDS was moved to its final destination, the cryostat. Once installed into the cryostat, final cable/channel/visual checks were made, followed by a full integration of the PDS into the ProtoDUNE-SP system.

All PDS modules were tested in the coldbox the same way, minus one PDS set (APA6) due to time constraints. Once the combination of APA + PDS module approval to proceed, the APA+PDs were installed one-by-one into the cryostat, along with all other detector components described in Chapter 5. Following the entire ProtoDUNE-SP Detector installation, the cryostat was filled with LAr and thus began the commissioning of the PDS in its final state.

6.3 Detector Commissioning & Operations

The Data Acquisition (DAQ) system is a central element of ProtoDUNE-SP, since it interfaces with the detectors’ readout electronics and external devices used for triggering (e.g., beam instrumentation, cosmic, PDS, etc.), with the Detector Control System (DCS), and with the offline computing. The DCS includes all the elements (hardware and software) that allow the correct operation of the detector. It is in charge of the monitoring and control of the detector and includes hardware and software elements that give information and access to the detector subcomponents. As ground lead for the PDS, I was responsible for integrating the PDS into the DCS and DAQ. This included power supply control and settings integration, channel-by-channel commissioning, testing, & calibration, and full DAQ and online monitoring integration with the entire ProtoDUNE-SP system.

In total, we installed 24 SSPs into 6 SSP crates, which was located on top of the ProtoDUNE-SP cryostat. Figure 6.18 shows a visual of said SSP crates, along with the cable trays and cable organization for a proper installation. Powering the SSP crates came from an external power supply, splitting the power into two different supplies: (1) high voltage (HV), which supplied the necessary voltage to power the photosensors (2) low voltage (LV), which supplied the necessary voltage to operate the SSPs. All Cat6 PDS warm cables, reading out all PDS modules, were
Figure 6.17: This figure shows the 24 SSPs installed into 6 SSP crates, which was located on top of the ProtoDUNE-SP cryostat. Within each SSP crate was an optical fiber DAQ patch panel, allowing for a SSP to integrate with the DAQ and DCS.

connected to their corresponding SSP via RJ-45 connector. These Cat6 cables allowed for biasing the photosensors from the SSP and an analog signal return to the SSP. Within each SSP crate was an optical fiber DAQ patch panel, allowing for a SSP to integrate with the DAQ and DCS. Therefore, communication and operation control of all PDS channels could be run through the DCS and DAQ, with the ability for continuous readout for all channels.

The next section will explain the DCS and DAQ controls and process for taking PDS data at ProtoDUNE-SP. For a more detailed explanation of the PDS commission and activation activities, please refer to our technical documents [82, 83].
6.3.1 Detector Control System and Data Acquisition

To begin proper communication between the DAQ and the PDS channels, all power supplies and proper connections must be linked and turned on correctly. Figures 6.17, 6.19 & 6.20 shows the DCS controls in a user friendly (GUI) format. I worked with the DCS + DAQ group in order to produce this user friendly interface, in order for DAQ shifters to learn and take data properly. Safety shutdown procedures were also implemented within the DCS controls, in case of light saturation due to the purity monitors (produced lots of light within the argon), overheating, grounding shorts, etc. In addition, we were able to implement upper limits to the power supplies on the back-end to where general users could not harm our PDS electronics.

As shown in Figure 6.20, each channel was calibrated individually. This thorough process, discussed in our technical document [82], allowed us to properly calibrate all PDS channels to approximately the same discriminator rates and gain. This allowed us to better characterized our PDS channels accordingly, as well as help the DAQ to optimize its free memory.
Figure 6.19: This figure shows the HV & LV controls for easy user friendly access.

Figure 6.20: SSP Setup and Readout GUI in the DCS. All channels for all SSPs can be biased and calibrated separately. This allowed us to better characterized our PDS channels accordingly, as well as help the DAQ to optimize its free memory.
Each PDS channel can be individually triggered by any of the following: a periodic timestamp trigger, a SSP-internal trigger based on a leading-edge discriminator local to the individual channel, or a SSP-external trigger from the timing system. If a SSP trigger is present, the channel will produce a data packet consisting of a header and a waveform of predefined length, which comprises a series of ADC values. The header contains bookkeeping information (e.g., module and channel numbers, timestamps, trigger type) and some calculated integral values for the waveform. Because the SSP trigger system is distinct from the global trigger, the unit of data produced when an SSP channel triggers is called a “packet,” and the term “trigger” refers to the global triggers only. The DAQ used a “SSP boardreader” to generate a fragment when a trigger produced by the timing system is observed. This fragment will contain all packets received from the SSP with timestamps in a window $\pm 2.5$ ms from the timestamp of the trigger. Therefore, when there is a global trigger, the DAQ retrieves the SSP header information from the SSP boardreader, syncing up with the correct timestamps.

In general, an SSP fragment will contain a fixed 12 packets with identical timestamps corresponding to the trigger time, one for each channel, and also an arbitrary number of additional packets generated when a channel’s discriminator (internal trigger) fires. It should be expected that a different number of packets will be observed for each channel within a given fragment. These SSP fragments are sent from the SSP boardreader to the DAQ for compressing, storage, and fractionally copied and preprocessed to the online monitoring system. Figure 6.21 shows a detailed overview of the DAQ data flow.

6.3.2 PDS Operations

Once modules were fully functional and fined tuned for proper triggering and data taking, the PDS was ready for real data runs. Overall, ProtoDUNE-SP has collected more than $10^6$ events in each of the following: beam data, cosmic data, random trigger data, and calibration data.
Figure 6.21: This figure shows an overview of the DAQ system and its interconnections with all sub-components. For PDS purposes, you can follow the SSP fragments being sent from the SSP boardreader to the DAQ for compressing, storage, and fractionally copied and preprocessed to the online monitoring system [26].

During ProtoDUNE-SP Beam physics runs, the DAQ had a data rate of 430 Gb/s, where this rate was mostly dominated by the TPC. The approximate data rate for the PDS was \(\sim 4\text{Gb/s}\), where \(\sim 3\text{Gb/s}\) came from the internal triggered within each global trigger. This led to the DAQ target trigger rate to be 25 Hz, with a readout window of 5 ms for both the TPC and PDS. After data compression, the typical data DAQ output bandwidth was \(\sim 6.5\text{Gb/s}\).

Following the PDS commissioning, I continued as the PDS lead for operations during the entire test-beam and calibration runs. This included contributing to full beam shifts, online monitor support, and being the sole on-call PDS expert. In addition, I contributed by training many collaborators in both the PDS in its entirety and new shifters running the DAQ.

Taking PDS data runs, such as noise runs, DCM calibration runs, stability runs, beam runs, cosmic runs, and bias scans were needed for the overall PDS effort and analysis. In order to take these specific runs, unique configuration files needed to be implemented. These configuration
Figure 6.22: This figure shows a snapshot of the PDS-DAQ runs for all data runs taken, starting from the coldbox measurements to the end of the beam runs.

Figure 6.23: This figure shows an example of the PDS online monitoring used during all PDS data taking, in order to verify that our PDS data taking ran smoothly. Displaying a live feed to monitor our data during a given run allowed us fundamental checks, such as persistent traces, rates, rms, etc.
**Figure 6.24:** This figure shows the Cosmic Telescope (right), which helped to verify calibration measurement taken with the DCMs, PDS technology comparisons, as well as possible calorimetry measurements. The schematic (left) labels the positions in red boxes where the Cosmic Telescope took data.

Settings included channel set bias & internal discriminator thresholds, time duration of readout per run, DCM-LED’s specific bias (for different light intensities), and DAQ configuration information that told the DAQ which components of which detectors were going to be implemented in the current data run. This process was well documented in my technical documents [84, 83], as well as a thorough spreadsheet of all PDS data runs (including coldbox runs) taken at ProtoDUNE-SP [85]. A snapshot of the list of runs documented is shown in Figure 6.22.

Online monitoring was used during all PDS data taking. Working with the DCS + DAQ group, we were able to display a live feed (needed) to monitor our data during a given run. Fundamental checks, such as persistent traces, rates, rms, etc., allowed us to verify that our PDS data taking ran smoothly. An example of this online monitoring is shown in Figure 6.23.
Following the Beam run, we installed a Cosmic Telescope. The Cosmic Telescope helped to verify calibration measurement taken with the DCMs, as cosmics are well understood. In addition, looking at vertical cosmic muon tracks along the ProtoDUNE-SP detector, would help with PDS technology comparisons, as well as possible calorimetry measurements. This Cosmic Telescope consisted of a 3-fold coincidence, using three individual scintillator paddles, as shown in Figure 6.24. The Cosmic Telescope was also integrated to the DAQ and multiple data sets were taken at different locations.
Chapter 7

ProtoDUNE-SP Analysis and Results

The ProtoDUNE-SP detector is a prototype for the first Far Detector module of the Deep Underground Neutrino Experiment (DUNE), and it incorporates full-size components for a liquid argon time projection chamber (LArTPC), with an active volume of $7.2 \times 6.1 \times 7.0 \text{ m}^3$. It was installed at the CERN Neutrino Platform in a specially-constructed beam that delivers charged pions, kaons, protons, muons and electrons with momenta in the range $0.3 \text{ GeV}/c - 7 \text{ GeV}/c$.

The experiment ran from September 2018, to July 2020, with beam operations running from October-December 2018. The data taken at ProtoDUNE-SP have enabled many useful measurements. These include TPC noise and gain measurements, $dE/dx$ calibration for muons, protons, pions and electrons, drift electron lifetime measurements; photon detector noise, signal sensitivity, efficiency, time resolution, and progress toward combined light + charge calorimetry measurements. The results will serve as a template for understanding how the beam studied in ProtoDUNE-SP particles will appear when produced during neutrino and/or other physics interactions in DUNE, and they will be an important reference in the analysis development toward LArTPC detectors, in general. In addition, the analysis work done on ProtoDUNE-SP will provide a real-world test bed for the development of algorithms for pattern recognition, event reconstruction and analysis, and they will be used to measure the cross sections of interactions of charged particles in LAr. Detector performance properties measured at ProtoDUNE-SP have met or exceeded the specifications for the DUNE Far Detector, in several cases by large margins.

This chapter will briefly discuss the overall analysis and results obtained from the ProtoDUNE-SP experiment, but will primarily focus on my contributions to the Photon Detection analysis and results. The overall goal of my studies is to examine the scintillation light signal in a large-volume LArTPC, in order to understand the physical properties and performance of the PDS, with the
outlook of contributing to the success of sensitivity measurements required for the physics program of DUNE.

7.1 ProtoDUNE-SP Overall Results

Results from ProtoDUNE-SP are described in detail in our published papers [44, 26, 24] and will be briefly summarized in this section. The detector’s high-level performance parameters from studies and findings are shown in Table 7.1, and are compared with the corresponding DUNE-SP Far Detector design specifications, as explained in Chapter 2. For each of the categories shown, the ProtoDUNE-SP performance meets or exceeds the DUNE specification, in several cases by a large margin. This successful performance demonstrates the effectiveness of the Single-Phase detector design and the execution of the fabrication, assembly, installation, commissioning, and operations.

Key highlights from the ProtoDUNE-SP experiment:

- The 3.6 m electric field in the TPC drift volume was stable at the nominal level of 500 V/cm with >99.5% of uptime during the data taking periods with beam and cosmics.

- A drift electron lifetime in LAr of 20 ms was achieved and was sustained for an extended period of data-taking. It reached approximately 89 ± 22 ms for the last day of beam data-taking. Therefore, the impurity in LAr was ∼ 3.4 ± 0.7 ppt oxygen equivalent. The DUNE specification for the impurity concentration’s to be less than 100 ppt O₂ equivalent.

- The TPC and cold electronics showed excellent signal-to-noise performance of 40.3, 15.1 and 18.6, for the collection, and two induction wires planes, respectively, after noise filtering and signal processing.

- The signal-to-noise ratios for the photon detectors range from around 6 for the ARAPUCA modules to 12 for the Double-Shift and Dip-Coated modules.

- The measured resolutions of the calibrated TPC and photon detector responses to protons, muons, electrons, and charged pions are similar to those in the simulations.
Table 7.1: ProtoDUNE-SP performance for main parameters and corresponding DUNE specifications.

<table>
<thead>
<tr>
<th>Detector parameter</th>
<th>ProtoDUNE-SP performance</th>
<th>DUNE specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average drift electric field</td>
<td>500 V/cm</td>
<td>250 V/cm (min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 V/cm (nominal)</td>
</tr>
<tr>
<td>LAr e-lifetime</td>
<td>&gt; 20 ms</td>
<td>&gt; 3 ms</td>
</tr>
<tr>
<td>TPC+CE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>(C) 550 e, (I) 650 e ENC (raw)</td>
<td>&lt; 1000 e ENC</td>
</tr>
<tr>
<td>Signal-to-noise (SNR)</td>
<td>(C) 48.7, (I) 21.2 (w/CNR)</td>
<td></td>
</tr>
<tr>
<td>CE dead channels</td>
<td>0.2%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>PDS light yield</td>
<td>1.9 photons/MeV</td>
<td>&gt; 0.5 photons/MeV</td>
</tr>
<tr>
<td></td>
<td>(@ 3.3 m distance)</td>
<td>(@ cathode distance - 3.6 m)</td>
</tr>
<tr>
<td>PDS time resolution</td>
<td>14 ns</td>
<td>&lt; 100 ns</td>
</tr>
</tbody>
</table>

- Three different photon detection technologies were implemented in the PDS and characterized with muon and electron beam data. The ARAPUCA technology showed 2% efficiency, the highest among the three, with a light response to EM energy deposit linear over the entire range of beam energies.

7.2 Overview of TPC Operations and Results

One core feat for the LArTPC of ProtoDUNE-SP was the demonstration of excellent ionization signal collection at its 3.6 m maximum electron drift distance (which corresponds to the distance between the cathode and anode planes) in the TPC. Previously, the longest drift distance in a large-volume LArTPC was accomplished by MicroBooNE, which operated a 2.5 m drift distance [53]. Increasing to a longer drift distance in a larger volume brings extra challenges with it. Argon ions and impurities within the argon are both capable of absorbing electrons on their way to the anode and therefore, the challenges increase with longer drift distance. With ProtoDUNE-SP’s
Figure 7.1: This figure shows a summary of the ProtoDUNE-SP beam run in late 2018. The nominal beam momentum (top, black), electron lifetime (middle) and high voltage status (bottom) over time (only high voltage disruptions exceeding 10 minutes are shown in red) [30].

advancement in cryogenics and purity filtration systems, including the successful operation of its HV system, we were able to achieve this 3.6 m drift distance.

7.2.1 ProtoDUNE-SP Operations

In July 2018, the commissioning activities had been completed and the purging and filling operations started. By mid September 2018, the detector was fully filled with LAr and ready for activation and running. On September 21, 2018, the HV on the cathode achieved for the first time its nominal value of 180kV (500 V/cm). ProtoDUNE-SP was able to measure the argon purity over time using a dedicated purity monitor and independently by examining TPC-crossing muon tracks. Figure 7.1 shows a detailed summary of the ProtoDUNE-SP conditions during its runs, including information such as beam momentum, electron lifetime, and high voltage status.
The three main sources of particles in ProtoDUNE-SP are from the incident beam particles referred to as primary particles, cosmic rays, and beam halo particles coming from the beamline and upstream sources. The detector simulation includes the propagation of these particles in LAr, their energy deposition, and various detector effects, described in Chapters 2 and 3. The simulation, reconstruction, and analysis framework used in ProtoDUNE-SP are based on the LArSoft software tool kit [86]. It is a software package widely used in LArTPC neutrino experiments based on C++ and ROOT [87]. It is commonly used for data analysis and it provides interfaces with the event generators for beam particles. ProtoDUNE-SP MC simulations include the generation of beam particles. Cosmic rays are simulated by CORSIKA and CRY generators [88, 89]. The generation of the primary beam particles in the H4 beamline (described in Section 5.2.1), their propagation, and possible interactions before the detector is done by the GEANT4 (based G4Beamline) tool [90] and FLUKA [91].

The total beam events recorded at ProtoDUNE-SP are shown in Table 7.2. Accurate measurements of the interactions of these particles allow for a more precise understanding of neutrino
Figure 7.2: The distribution of particles’ time of flight against reconstructed momentum from several runs at various beam reference momenta. The red curves are predictions for $e$, $\mu$, $\pi$, $K$, $p$ and deuterons ($d$) in order of increasing time of flight [44].

interaction signals in DUNE. Therefore, it is first essential that particle identification (PID) is well understood. ProtoDUNE’s beam line is designed to provide PID for the various particle types ($p$, $\mu$, $\pi$, $e$, $K$) comprising the beam. Depending on the beam momentum settings, different conditions are applied to the data from the beam line instrumentation to extract the particle types. Figure 7.2 is an excellent example of the precision we were able to achieve at ProtoDUNE-SP, showing the distribution of particles’ time of flight (TOF) against the reconstructed momentum from several runs.

As discussed in Section 3.2.1, the LArTPC principle of operation relies on the conversion of ionization electrons to an electric signal on the sensing wire planes. The three wire planes instrumented with readout electronics in ProtoDUNE-SP are parallel with respect to each other. The collection plane wires and the two induction planes are at an angle of $\pm 35.7^\circ$ with respect to vertical. The reconstruction of ProtoDUNE-SP events from beam particles or cosmic rays is separated into two
Figure 7.3: This figure shows an overview of the reconstruction paradigm that was used at ProtoDUNE-SP [24].

steps: (1) hit finding (2) pattern recognition. An overview of the reconstruction paradigm is shown in Figure 7.3. The hit finding uses an algorithm to fit Gaussian shapes to peaks in the waveforms; each hit is associated with a fitted peak and a time stamp. The signal shapes can vary as a function of the ionisation track orientation with respect to the wire plane orientations (induction/collection plane). An example of this is shown in Figure 7.4, ProtoDUNE-SP’s first cosmic ray track observed from ProtoDUNE-SP’s online monitor on September 21, 2018. The second step is pattern recognition, and is performed via the Pandora software package [92], which has been successfully used in MicroBooNE [53]. For reconstruction of ProtoDUNE-SP data, minor modifications were added since the events under study are not from neutrinos interactions but rather single particles from a charged particle beam, with a well-defined location in the detector. An example of an event reconstruction is shown in Figure 7.5, ProtoDUNE-SP’s first observed beam particle on October 2, 2018, using the offline event display.
Figure 7.4: This figure shows first cosmic ray track observed from ProtoDUNE-SP on the online monitor on September 21, 2018. The track is viewed by the collection y-z plane (y-coordinate: height of detector; z-coordinate: following the particle beam) [93].

Detector signals, both real and simulated, are reconstructed using the Pandora framework [94]. Signals from the sensing wires are grouped to hits and clustered, and then use Pandora specific algorithms to reconstruct the particle trajectory, energy, interaction points, and associate outgoing particle daughters. Figure 7.6 is an excellent example of the precision we were able to achieve, showing the reconstructed dE/dx distributions, using ProtoDUNE-SP’s analysis procedures. For other TPC and physics development and analyses, please refer to our ProtoDUNE-SP published papers [44, 26].

7.3 Scintillation Light Detection

Scintillation light detection is needed for non-beam event timing, such as atmospheric neutrinos, proton decay, and supernova detection. It also provides a prompt signal for microsecond event time determination, which improves the LArTPC’s spatial localization, enables accurate ionization-signal-attenuation, and even provides calorimetry. As mentioned in Chapter 6, I spent a significant amount of time with instrumentation, commissioning, and operations for the Photon Detection
Figure 7.5: This figure shows the ProtoDUNE-SP’s first event from beam data observed on October 2, 2018, using the offline event display [93]. The top three (colored) panels show the collection plane (top), and the two induction planes (bottom). The bottom (black and white) panel shows an extracted raw waveform from an induction wire.

ProtoDUNE-SP includes novel photon detector designs, which embeds the photon detectors within the APAs in order to collect scintillation light from ionized LAr—see Section 3.2.2. Due to the small available active area, the photon detectors are required to be highly efficient for detecting single photons, without inducing any background noise to the TPC. For the ProtoDUNE-SP experiment, the PDS modules are sensitive to photons arriving from the direction of the cathode. As discussed in Chapters 5 and 6, three different photon collection technologies were implemented. In each technology, incident LAr scintillation (128 nm) photons are converted into the visible, via wavelength shifting material. The visible light is then trapped within the modules, which is then collected by a photosensor array of SiPMs.
Figure 7.6: This figure shows sample MC to data comparisons made from ProtoDUNE-SP data. Left: shows the distribution of dE/dx values of all hits on the collection plane from the selected beam pion candidates. Right: shows the distribution of dE/dx distribution for the stopping muon sample [44].

My core analysis work revolves around the development of Scintillation Photon Detection technologies for DUNE. Specifically, it aims to understand the underlying characteristics, performance, and response of the detectors, in order to properly understand scintillation signals when exposed to a multi-GeV charged particle beam. The next sections will dive into how we characterized our photosensors/photon detectors, how we define and calculate the performance, and how we use scintillation light for energy reconstruction and resolution. All are required to be understood for the necessary physics for DUNE.

7.4 Photon Detector Characterization

As discussed in Section 5.3, individual readout of numerous SiPMs is quite costly. Therefore, arrays of photosensors are passively ganged together in parallel forming large-area single channels to reduce the final DAQ channel count for ProtoDUNE-SP. A variety of silicon photomultipliers models have been deployed to explore the performance of different vendor options for the final
Table 7.3: Numbers of each type of PDS module installed in ProtoDUNE-SP, and the numbers of sensors per channel and channels per module [44].

<table>
<thead>
<tr>
<th>Ganged-Channel Type</th>
<th>N.Sensors/Channels</th>
<th>N.Channels/Module</th>
<th>N.DipCoated Modules</th>
<th>N.DoubleShift Modules</th>
<th>N.ARAPUCA Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-S-SiPM</td>
<td>3</td>
<td>4</td>
<td>29</td>
<td>29</td>
<td>-</td>
</tr>
<tr>
<td>3-H-MPPC</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>12-H-MPPC</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Of the 60 PDS modules installed into the ProtoDUNE-SP detector (see Figure 6.13), 29 Dip-Coated modules and 29 Double-Shift modules contain four groups of three photosensors ganged in parallel at one end of each module to detect trapped converted photons. Each module array contains 12 SiPMs passively ganged in groups of three and read out as four independent channels. The two ARAPUCA modules include 6 or 12 photosensors within each of the sixteen sub-modules, with a total of 12 SiPMs\(^1\) ganged in parallel within a single DAQ channel.

It is important to properly characterize each photon detector in order to determine its performance and response. The next sub-sections will go over the characteristics of the photon detectors used in ProtoDUNE-SP, such as photosensor signals, single photo-electron calibration, signal-to-noise, light calibration, after-pulsing and cross talk, and stability over time.

### 7.4.1 Photosensors

Table 7.3 details the number of photosensors used per module, ganging type, and the total number of each technologies installed in ProtoDUNE-SP. Three silicon photosensor models, each with an active area of \(6\times6\ \text{mm}^2\), are employed: the SensL SiPM MicroFC-60035-SMT (35 \(\mu\text{m}\) pixel size) and\(^1\)

\(^1\)The ARAPUCA modules employ SiPMs from Hamamatsu Photonics Corp, which markets them under Multi-Pixel Photon Counters (MPPCs).
two types of Hamamatsu MPPC S13360-6050 (50 µm pixel size) - the CQ-type (Quartz windowed for Cryogenic application) and the VE-type (through-silicon via). The arrays formed by three SensL SiPMs are indicated in the following as 3-S-SiPM, those formed by 3 Hamamatsu MPPCs (VE-type) are indicated as 3-H-MPPC, and those with 12 Hamamatsu MPPC (CQ-type) as 12-H-MPPC. Each of Double-Shift & Dip-Coated Lightguide module is read out by four channels, each containing 3 passively ganged photosensors, labeled either 3-S-SiPM or 3-H-MPPC. Each of the 12 cells of the ARAPUCA module is read out by one 12-H-MPPC channel.

Signal extraction and noise evaluation from the recorded waveform (2000 time samples, 6.67 ns sample period) is made on an individual event basis. Trigger time (global or SSP internal trigger) is at fixed position in the waveform, as discussed in Chapter 6.3. Typical recorded waveforms are shown in Figure 7.7. The mean of the pedestal distribution was determined from a pre-sample portion of the waveform before the trigger, and gives the baseline value (in ADU) and the spread (σN) is an estimate of the noise in the recorded event. After baseline subtraction the charge of the signal (in ADU × time tick [tt] units, equivalent to number of electrons or fC) is evaluated by integration of the portion of the waveform starting from the trigger time and extending over a 7 µs time window—each time tick being 6.67ns. De-noising algorithms, preserving the signal rise time and integral, can be applied to more precisely evaluate the max amplitude in the same window corresponding to the photo-electron current of the signal (in ADU or µA). Photosensors for each of the 3 and 12-ganged channels were pre-selected based on minimal difference in their nominal breakdown voltage (at warm temperature) from data sheets. All sensors in a channel are biased at the same common voltage V_B, which enables the photosensors in a given channel to all operate in similar working conditions.

A small number of channels, 16 of 248, showed some anomalous readings and are described in Table 7.4. There were 2 that appeared to be disconnected, since the earliest tests. There were 2 that appeared to have some anomalous response to light signals. The remainder appear to be
simply dead, as though they were not connected. Therefore, these anomalous channels were ignored during the analysis.

7.4.2 Photo-electron Calibration

Each of the three types of photosensors (3-S-SiPM, 3-H-MPPC, 12-H-MPPC) used in ProtoDUNE-SP are calibrated similarly. A detector calibration pulser LED is flashed synchronously with the data acquisition, as shown in Figure 6.14. A typical waveform for a passively 3-ganged SensL SiPM, shown in Figure 7.7, will have a noise RMS on the order of a few ADCs, with a recovery time of about a microsecond. The digitized waveform collected during the LED pulse is baseline subtracted and the detected charge distribution is measured by integrating the waveform. The integration limits used for ADC charge/avalanche calculations were in the range 7µs to 10.3µs. The pedestal is calculated by averaging a large sample of baseline values outside the integration window. To account for the pedestal when integrating the waveform event, we subtract (the pedestal value \( \times \) the integration window) from the integrated signal.
<table>
<thead>
<tr>
<th>Ch.#</th>
<th>Sensor</th>
<th>Factory</th>
<th>Module</th>
<th>Run#</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>3749</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>36</td>
<td>A1</td>
<td>FNAL</td>
<td>DipCoated</td>
<td>4116</td>
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<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>49</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>6225</td>
<td>-</td>
<td>Gain issue</td>
<td>Gain issue</td>
<td>Gain issue</td>
</tr>
<tr>
<td>51</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>8184</td>
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<td>Gain issue</td>
<td>Gain issue</td>
<td>Gain issue</td>
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<tr>
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<td>A1</td>
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<td>DoubleShift</td>
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<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>62</td>
<td>A1</td>
<td>FNAL</td>
<td>DipCoated</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>65</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
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<tr>
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<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>Disconnect</td>
<td>Disconnect</td>
<td>Disconnect</td>
<td>Disconnect</td>
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</tr>
<tr>
<td>75</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>Disconnect</td>
<td>Disconnect</td>
<td>Disconnect</td>
<td>Disconnect</td>
<td>Disconnect</td>
</tr>
<tr>
<td>82</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>101</td>
<td>A1</td>
<td>FNAL</td>
<td>DipCoated</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>110</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>119</td>
<td>A1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>156</td>
<td>C1</td>
<td>IU</td>
<td>DoubleShift</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
<tr>
<td>160</td>
<td>C1</td>
<td>FNAL</td>
<td>DipCoated</td>
<td>-</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
<td>Dead</td>
</tr>
</tbody>
</table>

Table 7.4: Listing of the channels for the protoDUNE-SP detector that are considered bad, why, and when they were first seen. No channels have changed since cooling the detector. These anomalous channels were ignored during the analysis.
Figure 7.8: This figure shows the Charge/Integral (top row) and Current/Amplitude (bottom row) for a typical distribution for a 12-H-MPPC channel ($V_B = 48$ V) and for a 3-S-SiPM channel ($V_B = 26$ V) [44].

Typical charge (signal integral) and current (signal amplitude) distributions under pulsed LED illumination and nominal $V_B$ setting for operation are shown in Figure 7.8 for a 3-S-SiPM channel (left column) and from a 12-H-MPPC channel (right column). The multi-peak structure corresponds to detection of 0, 1, 2, ... photo-electron (PE) induced avalanches. The clear peak separation confirms good sensitivity to single PE detection for either the 3 and 12-ganged channels. The spread around the peaks in the charge spectra (top row in Figure 7.8) is partly due to over-voltage difference among sensors in the array. The lopsided distribution around the peaks in the signal amplitude spectra (bottom right panel in Figure 7.8) may be due to secondary avalanches from after-pulse and cross-talk in the sensors, and is more visible in the H-MPPC due to the faster
Figure 7.9: Gain as a function of applied bias voltage for SiPM channels (left) and for MPPC channels (right). Linearity of individual channel response is shown by the linear fit (red line) across the points at different bias voltage setting. The intercept of the fit line provides a direct evaluation of the breakdown voltage at LAr temperature for each 12-H-MPPC and 3-S-SiPM photosensor [44].

The gain as a function of bias voltage is shown (black dots) in Figure 7.9 for some of the 3-S-SiPM (left) channels and 12-H-MPPC channels (right). The gain response to varying $V_B$ is very uniform channel by channel, as indicated by the slopes (red lines through dots) in Figure 7.9. The y-intercept with the horizontal axis, that defines the actual break-down voltage $V_{bd}$ at LAr temperature of the multi-sensor channels.

The bias settings used for PDS operation were $V_B = 26$ V for the 3-S-SiPM and $V_B = 48$ V for the 12-H-MPPC. In both cases, the photosensors are operating within the manufacturer range. The two types are operated at different over-voltages $V_{oV} = (V_B - V_{bd})$ in the range (3.3 - 4.2) V for the 12-H-MPPC channels and (5.0 - 5.5) V for the 3-S-SiPM channels. Gains are correspondingly higher, by a factor $\sim 2$, for the 3-S-SiPM channels as indicated in Figure 7.9 (left).
7.4.3 Signal to Noise of Photosensors

Signal to Noise ratio (SNR) is a good performance metric for the characterization of the photosensor component of the PDS during normal operating condition. The SNR of the individual channel (3 or 12 photosensors in parallel) at the reference bias voltage setting is here defined as:

\[ SNR = \frac{\mu_1}{\sigma_0} \]  

(7.1)

where, referring for example to Figure 7.8 (top row), the signal \( \mu_1 \) is the mean value from the Gaussian fit of the 1-PE peak (the minimal detectable signal), and the noise is evaluated from the Gaussian spread, \( \sigma_0 \) of the 0-PE peak. The SNR for all channels of the three types is shown in Figure 7.10. Values for the 3-S-SiPM channels of the double shift and dip coated bar modules are in the 10 to 12 SNR range, around 8-9 for the 3-H-MMPC channels, and around 6 for the 12-H-MPPC channels of the ARAPUCA modules. The SNR as defined in (7.1) is directly proportional to the gain and the higher SNR shown by the 3-S-SiPM channels is primarily due to their higher \( V_{ov} \) setting adopted for operation.

Figure 7.10: Signal-to-Noise Ratio (SNR) for the 3-S-SiPM channels (left), for the 3-H-MPPC channels (center), and for the 12-H-MPPC channels (right) [44].

7.4.4 Light calibration

The means extracted from fits of Gaussian functions to the significant peaks are used to determine the charge per avalanche for each group (channel) of photon sensors. In order to properly illuminate
all devices many runs were needed at varying intensities of the flasher in order produce a suitable
distribution of light in each photon sensor group.

Calibration of the readout system requires measuring the response to a uniform incident light
signal. The detector calibration module is used to provide the source of light for the calibration,
as discussed in Section 6.2.3. There are many ways to perform this type of calibration. The
method used for ProtoDUNE-SP was to use the Poisson distribution of a low level light signal. The
important feature used is the probability of getting a zero for a given light level.

The average number of detected photons \( n \) per light flash follows the Poisson distribution
with \( \lambda \), the expected mean number of photons detected per flash, whose value is directly related to
the probability of detecting zero photons in that flash. The Poisson formula:

\[
P(n) = \frac{\lambda^n e^{-\lambda}}{n!}
\]

with \( P(0) = e^{-\lambda} \rightarrow \lambda = -\ln P(0) \) (7.2)

The probability \( P(0) \) can be estimated by the relative frequency of detecting zero photoelectrons
in many LED trials (0-PEs detected = 0-photons emitted), and from this the mean number of
photons detected per flash is inferred:

\[
\lambda = -\ln \left( \frac{N_0}{N_{\text{Tot}}} \right)
\]

(7.3)

where \( N_0 \) is the observed number of counts under the zero-PE peak (1st peak in the charge distri-
bution of Figure 7.8 - top row) and \( N_{\text{Tot}} \) is the number of LED flashes in the calibration run.

In order to use this method there has to be a sufficient probability of observing 0, which means
the light level has to be carefully adjusted to ensure proper illumination of each device. In addition
to this, the measured rate has to be corrected for the background rate of of single photoelectron
events that occur in the trigger window. The background rate is calculated from the part of the
waveform before the DCM was triggered [95].

The photosensor response to \( \lambda \) detected photons, estimated by equation (7.3), is the mean charge
output per flash \( \langle Q \rangle \) in the calibration run (average of the distribution shown in Figure 7.8 - top
Figure 7.11: Charge signal per detected photon (blue points) and charge signal per avalanche (black points) as a function of applied over-voltage $V_{ov}$ for a typical 3-S-SiPM channel (left) and 12-H-MPPC channel (right). The difference is due to the correlated noise contribution, mainly from afterpulse and crosstalk in neighboring microcells of the photosensor. The vertical dotted line at the operation over-voltage set point indicates the gain $g_i$ and the calibration factor $c_i$ used in data analysis for the $i$-th channel shown in the figure [44].

The charge issued when an incident photon is detected is expected to be, on average, larger than the single-avalanche induced charge. The comparison of the charge per photon detected (calibration factor $c_i$ - blue line) and charge per avalanche (gain $g_i$ - red line) as a function of the applied over-voltage $V_{ov}$ is shown in Figure 7.11 for a typical 3-S-SiPM channel (left) and 12-H-MPPC channel (right). The difference is due to the correlated noise contribution to the signal formation in the photosensor. This is found to grow exponentially with increasing voltage.

### 7.4.5 Afterpulses and Crosstalk

The calculation of the gain and charge per avalanche allows the calculation of the crosstalk and afterpulse probability for the photon detectors. A common feature of silicon photosensors is the
generation of avalanche pulses subsequent to a primary event. The avalanche of a single microcell in a device has a finite probability of inducing an avalanche in neighboring microcells (optical crosstalk), and/or of re-triggering itself before the microcell is fully recovered (afterpulse). These effects can be measured by taking the ratio of the average detected charge per photon and the charge per avalanche.

Figure 7.12: Afterpulse and crosstalk contribution to the photosensor signal expressed by the average number of avalanches generated per detected photon for the 3-S-SiPM channels (left), for the 3-H-MPPC channels (center), and for the 12-H-MPPC channels (right) [44].

The rate of these secondary pulses increases at higher gain settings. The correlated noise due to these effects is a well-known limiting factor for a precise photon counting with silicon photodetectors. The measurement of the charge per photon detected (the calibration factor $c_i$, defined in Section 7.4.4) and the charge per avalanche (the gain $g_i$, defined in Section 7.4.2) allows the calculation of the crosstalk and afterpulse probability for each photosensor by the ratio $c_i/g_i$ in units of [Ava/Ph], average number of avalanches per photon detected. This ratio is sensitive to the over-voltage on the photon detector and can be used to monitor for changes in the operating characteristics of the photosensor as a measure of the stability of the PD system. Figure 7.12 shows the measured avalanche/photon value for each channel in the PDS. An average of $\sim$1.3 Ava/Ph is found for the 3-S-SiPM channels and the 12-H-MPPC, while a larger factor $\sim$1.6 Ava/Ph characterizes the 3-H-MPPC channels.
Figure 7.13: Stability of the photosensor response over time: gain stability (charge signal per avalanche) for typical 3-S-SiPM channel (left) and 12-H-MPPC channel (right), from calibration runs performed over \( \sim 100 \) days of operation. The shaded band corresponds to a \( \pm 5\% \) gain interval. Gain variations over time are contained well within the band. Statistical error bars are small, not visible inside the band [44].

### 7.4.6 Response stability over time

The photosensor gain, calibration factor, and the size of the afterpulse and crosstalk component of the signal can be used as a system monitor. Thus, we looked for any drift in these parameters as an indication of instability in the system. As mentioned in Section 6.3, I developed many automated calibration runs for these purposes. Therefore, calibration data was taken at various times during operations in order to provide measurements that monitored the system stability as a function of time. Figure 7.13 shows the value of the gain for typical 3-S-SiPM channel (left) and 12-H-MPPC channel (right) channels over the course of several months. Within the uncertainties of the measurements, neither the gain nor the other parameters were found to be drifting over time for any of the sensors used in the ProtoDUNE-SP Photon Detector System.
7.5 **Photon detector performance**

The PD modules are exposed to scintillation light originating along the trajectories of ionizing particles within the drift volume, as discussed in Section 3.2.2. A fraction of the emitted photons incident the optical surface of any given PDS module, and a charge signal is recorded, proportional to the number of photons detected by the photosensors of the module. The detection efficiency $\epsilon_D$ of a PDS module is defined here as the ratio of detected photons to incident photons. Test-beam data from particles of known type, energy and incident direction in the LAr volume are used to determine $\epsilon_D$ and thus evaluate the performance of the different detection technologies implemented in the PDS.

7.5.1 **Simulation of Scintillation Light**

For each beam event, the number of detected photons $N_j^{\text{Det}}$ is evaluated from offline data reconstruction (baseline subtraction, waveform integration and charge-to-photon conversion) for each of the 30 detector modules located in the three APAs viewing the beam side—15 Double-Shift, 14 Dip-Coated and 1 ARAPUCA module. A Monte-Carlo simulation of test beam events is used for extracting the corresponding number of photons incident $N_j^{\text{Inc}}$ on each PDS element (light-guide module or cell in the ARAPUCA module). This simulation is performed with the LArSoft toolkit [86], which has a detailed description of the geometry of the ProtoDUNE-SP detector, including a proper description of the materials and the positions of the TPC components surrounding the LAr volume (APA, CPA, FC, as shown in Figure 7.14). Simulation of beam events is performed with standard GEANT4/LArG4 generator within LArSoft. This accounts for the well known features of scintillation in liquid argon ensuing ionization processes [96].
Figure 7.14: 3D event display made with the Wire-Cell BEE display [97] showing data from a 7 GeV/c beam muon crossing the whole TPC volume, fully reconstructed by the LArTPC. Only tracks inside a predefined sub-volume (red box) are shown. The beam muon track enters near the cathode and propagates along the beam direction about $10^\circ$ downward and $11^\circ$ toward the anode plane. Ten PDS modules are located in each APA frame. The Double-Shift Lightguides are shown in green, Dip-Coated Lightguides are in blue, and the ARAPUCA module in orange [44].
**Photon emission**

The emission spectrum is a narrow band in the Vacuum-UV (VUV) wavelength range peaking around $\lambda = 128$ nm (FWHM $\simeq 6$ nm), exponentially distributed in time with two very different time components (fast $\sim 5$ ns and slow $\sim 1.3 - 1.4$ $\mu$s, with intensity ratio 0.3 in case of minimum ionizing particles). Electric fields applied to the LAr medium affect the intensity of scintillation emission. At 500 V/cm (ProtoDUNE-SP operation), a photon yield of $2.4 \times 10^4$ photons/MeV for minimum ionizing particles is assumed in simulations, 60% of the maximum yield measured at zero field. The relative uncertainty on the photon yield value is 8.5% [98]. The photon yield dependence on increasing linear energy transfer, the rate of energy deposited by ionizing particles, is not included in the current simulation.

**Photon propagation**

LAr is transparent to its own scintillation light. However, during propagation through LAr, VUV photons may undergo Rayleigh scattering, absorption from residual photo-sensitive impurities diluted in LAr and reflections at the boundary surfaces that delimit the LAr volume. In the MC simulation, the Rayleigh scattering length, the reflectivities of materials for VUV photons, and the absorption length as a function of the impurity concentration are parameters that are fixed at their best estimates from existing data. Tracking each of the large number of VUV photons emitted in an event using Geant4 is computationally expensive, so a pre-computed optical library is used to look up the probability that a photon produced at a particular location in the liquid argon volume is detected by a specific PDS channel. In order to create the optical library, the liquid argon volume is segmented into small sub-volumes, called voxels, of size $\sim 6 \times 6 \times 6$ cm$^3$. For each voxel, a large number (of order $5 \times 10^5$) of VUV photons is sampled with an isotropic angular distribution. All photons are tracked using Geant4, recording how many reach the sensitive area of each optical detector. In the simulation used to create the optical library, the Rayleigh
scattering length for VUV photons in liquid argon is assumed to be 90 cm, according to the most recent experimental determination [99, 100]. Due to the high level of purity during the beam run (Oxygen equivalent impurity concentration < 100 ppt), absorption by impurities is assumed to be negligible. Light reflection at VUV wavelength is low for perfectly polished metal surfaces (20% or less) and effectively null for any other material. The actual reflectance of the (extruded, non polished) profiles of the field cage surrounding the LAr drift volume is unknown and therefore it is set to zero in the current simulations. Once the library is created, ProtoDUNE-SP detector simulation jobs retrieve information from the library when the trajectory of an ionizing particle in the LAr volume is simulated by Geant4, converting the number of emitted photons from energy deposited in each voxel directly into the number of photons impinging upon the area of each PD module coming from this given voxel. The uncertainty on the rate at which photons arrive at the detector after photon transport is dominated by the uncertainty on the Rayleigh scattering length. Neglecting reflections at the LAr volume boundaries is expected to be a subdominant effect. A relative uncertainty of 5% is assigned to the number of photons incident on the detector surface by varying the Rayleigh length by 20% around the nominal value in the simulation.

**Photon transmission at the anode plane**

The optical surfaces of the PD modules lie immediately behind the four wire planes of the TPC and a fifth (grounding) plane made by the woven metallic mesh stretched across the APA frame (see Section 3.2.1). A correction is applied to account for the light transmission through this series of parallel planes, which is not included in the detector simulation in LArSoft. The geometrical transparency of the mesh is 85% (percentage ratio of opening to total area, function of wire gauge and pitch). The transparency is reduced to 75% when the TPC wire planes above the mesh plane are also considered. This corresponds to the transmission upper value for orthogonal incident light.
Figure 7.15: Schematic diagram illustrating photons impinging on a TPC wire plane (left) where the wire pitch $p$, the wire gauge $d$, and the incident photon angle ($\gamma$) are defined. On the right, the map of transmission – color scale from 0 to 1 – through the set of parallel planes (TPC wire planes and the mesh) as a function of the polar angles $\theta$, $\phi$ of the incident photon direction (the planes lie in the $(y, z)$ plane, $\theta = \gamma$ when $\phi = \pm \pi/2$) [44].

Transmission at any angle is then obtained based on a geometrical model, illustrated in Figure 7.15. This simplified geometrical model is used in which VUV photons intercepting a wire of the mesh are absorbed (no reflection). The transmission coefficient shows a dependence on the polar angle of incidence ($\theta$) almost flat with $T=0.75-0.7$ for photons incoming with $\theta < 45^\circ$ and then decreasing above that angle. Only a small modulation in the azimuthal angle $\phi$ is expected across the whole range due to the geometrical orientation of the wires and mesh planes ($\phi = \pm 35.7^\circ$, $0^\circ$, $90^\circ$) and the gauge per pitch ratios ($d/p$).

A stand-alone simplified MC simulation is then performed to evaluate the transmission of light from beam events. Optical photon emission is sampled over straight trajectories crossing the LAr volume along the beam direction, nearly representing beam muon tracks, or sampled according to a spatial parametrization of electromagnetic showers, representing the longitudinal and transverse energy deposition from incident beam electrons.
Figure 7.16: The distribution of particles’ time of flight against reconstructed momentum from several runs at various beam reference momenta. The red curves are predictions for $e$, $\mu$, $\pi$, $K$, $p$ and deuterons ($d$) in order of increasing time of flight.

After photon propagation to the APAs, the angular distribution of incident photons on each PD module is folded with the transmission map to obtain the transmission coefficients for beam muons and beam electrons. These coefficients were found to be in the 65-71% range, depending on the position of the PD module. The relative uncertainty on the transmission coefficients is evaluated to be 7% (one-sided) to account for the simplified assumptions in the model (no reflection). The transmission coefficients for each module so determined are then used to scale down the number of photons arriving at the APA from the Geant4 MC simulation of the beam events into the actual number of photons $N_{\text{Inc}}^j$ incident on the surface of the PD module behind the APA.
7.5.2 Efficiency

Muon and electron samples runs at different beam momenta were used for the efficiency calculation. Runs with beam momentum settings from 2 to 7 GeV/c were used for this, as the PID and energy deposition is well understood and enough for light yield to reach all PDS modules. The PID information from the beam instrumentation and the recorded light signals passing quality cuts are fully reconstructed (\(O(10k\) events/sample) for each run). Beam line instrumentation provides PID for various particle types (p, e, \(\pi\), k, \(\mu\)), and is shown in table 2 in [44].

The ambiguities in distinguishing pions and muons from electrons at 6 and 7 GeV/c are solved using the TPC track reconstruction. Looking at beam events starting shape, the signature given by Pandora, a multi-algorithm approach to automated pattern recognition [92], classifies the events as (showers starting) electrons and (track starting) pions and muons. Finally scintillation light spectra analysis allows to recognize muons from pions, for beam events of 2, 3, 6, and 7 GeV/c. Since muons with momentum \(>1.5\) GeV/c escape the volume of the TPC, they deposit less energy than pions with a completely different track geometry. Figure 7.16 gives an example of the light yield seen by the Double-Shift modules along the vertical of APA3 (closest to beam), as a function of beam momentum (2 - 7GeV/c). For a better physical view of the photons collected in space, please refer to the green labelling in Figure 7.14.

Correspondingly, Monte Carlo runs were generated with muons or electrons entering the TPC volume from the beam-plug with the same momentum (nominal value and spread) and direction to reproduce the features of the H4-VLE beam line (see Section 5.2.1). The MC samples were generated with the same number of triggers as were collected in the corresponding data samples. For each run the MC distribution of the number of photons in the event incident on the \(j\)-th PDS module and the distribution from real data sample of photons detected by the same module are extracted.
Figure 7.17: ARAPUCA cell efficiency as determined from beam muons. Cells are of two types with the last four cells (channels \(j = 9, \ldots, 12\)) having double size but equal number of photosensors than the first eight. Left: average number of detected photons with beams at different momenta. Center: average number of photons incident on the cell surface from MC simulation of electron and muon beams at corresponding momenta. Right: efficiency of the cell from the detected-to-incident ratio. Statistical error bars are small, not visible inside the symbols [44].

Muon data

The mean value \(\langle N^\text{Det}_{j}\rangle\) of the detected photon distribution from the muon data samples with beam momenta of 2, 3, 6 and 7 GeV/c (open circles of assigned color) are displayed in the left panel of Figure 7.17 for each of the 12 cells of the ARAPUCA module located in APA 3 of the PDS beam side. The mean values \(\langle N^\text{Inc}_{j}\rangle\) of the photons incident on the cell surface from the MC muon event samples is shown in the center panel. Statistical errors are small (few per-mille relative to the mean values, not visible inside the symbols), systematic uncertainties not shown in the figure are discussed later in this section. The detection efficiency \(\epsilon_{j} = \langle N^\text{Det}_{j}\rangle/\langle N^\text{Inc}_{j}\rangle\) given by the ratio of the two mean values are shown in the right panel, for each cell at all momenta.

For the Double-Shift and Dip-Coated Lightguide modules in the PDS beam side, the number of detected photons and incident photons were evaluated in the same manner from the same beam muon samples (data and MC runs with beam momenta of 2, 3, 6 and 7 GeV/c). The efficiency from the ratio of the detected to incident photons is shown in Figure 7.18. The left panel showing the
Figure 7.18: This figure shows the efficiency results for the PDS beam side Double-Shift and Dip-Coated Lightguide modules. The left panel showing the 15 Double-Shift Lightguide modules in APA3, 2 and 1 and the 14 Dip-Coated Lightguide modules shown in the right panel. Statistical error bars are small, not visible inside the symbols [44].

15 Double-Shift Lightguide modules in APA3, 2 and 1 and the 14 Dip-Coated Lightguide modules shown in the right panel. Statistical error bars are small, not visible inside the symbols. The locations of APAs 1, 2, and 3 in the ProtoDUNE-SP detector are shown in 3D in Figure 7.14.

Muons at all incident momenta are energetic enough to cross the entire LAr volume and exit from the downstream side (see Figure 7.14). Cells in the ARAPUCA module corresponding to channels \(j = 1, \ldots, 12\) are ordered along the \(z\) axis with the upstream cell\#1 at the beam entry point \((z = 0)\) into the LArTPC volume. The number of detected photons increases from cell to cell along \(z\) due to the increasing visibility of the muon track from the cells deeper into the LAr volume. In every cell the number of detected photons is observed to increase with incident muon beam momentum (open circles of different color in Figure 7.17) due to the increase in the energy loss along the track for more energetic muons. This is better shown using the ARAPUCA cells for a throughgoing muon, rather than adjacent Lightguide modules, as the pitch between the cells are essentially zero.
Cells in the ARAPUCA module are of two types: the last four cells (channels \( j = 9, \ldots, 12 \)) have double size active area, but equal number of photosensors than the first eight. The high step in the number of collected photons \( N_j^{\text{Inc}} \) at \( j = 9 \), shown in Figure 7.17 (center panel), reflects the double geometrical acceptance of these cells. A smaller step is observed in the detected photons \( N_j^{\text{Det}} \) (left panel). Further, the detection efficiency is shown to be about half (right panel), which follows the active area-to-photosensor correlation.

The efficiency of the Double-Shift and Dip-Coated Lightguide modules is more-or-less consistent. It should be noted that these efficiency calculations do not involve a proper comparison between the ARAPUCA and Lightguide modules, when incorporating active area-to-photosensor coverage, as it is not a simple conversion due to the attenuation of internally reflected optical photons. As a crude characterization, As an example, a factor of two can be gained by instrumenting both ends of the Lightguide modules, and an even greater factor if populating more photosensors along the long-side of the lightguide bar.

**Electron data**

Electrons with beam momenta of 2, 3, 6 and 7 GeV/c provide data samples for a second independent set of efficiency measurements. Electrons deposit all their incident energy in showers localized in a limited portion of the LAr volume, unlike muons on long, throughgoing tracks, as shown in Figure 7.24 with a 3D display of 7 GeV/c beam electron event. The ARAPUCA module is shown for reference as it is unique in APA3, as well as nearly at the same height as the incoming beam.

The light response of the Double-Shift Lightguide modules with electron beam momenta of 3, 6 and 7 GeV/c are shown in Figure 7.19, excluding electron data at 2 GeV/c and modules in APA1. There are statistical limitations on the visibility values of the photon library used for \( N_j^{\text{Inc}} \) estimates for sensors positioned at APA1 (farther away from shower), and lower light levels in the 2 GeV/c range. For any given beam energy (open circle colors in the plots), the distribution of the detected
Figure 7.19: Electron events with 3 to 7 GeV/c were considered for the Double-Shift Lightguide efficiency studies. Left: average number of detected photons with beams at different momenta. Center: average number of photons incident on the cell surface from MC simulation of electron and muon beams at corresponding momenta. Right: efficiency of the cell from the detected-to-incident ratio. Statistical error bars are small, not visible inside the symbols [44].

The number of detected photons exhibits a shower-like longitudinal profile, as indicated by the two sets of the triangular peaks $N^\text{Det}_j$ & $N^\text{Inc}_j$, centering around the center of the APAs. In addition, the number of detected photons is also clearly correlated with the shower energy, increasing with higher momentum.

Similarly, the Dip-Coated and ARAPUCA modules efficiency results are shown in Figure 7.20. The Dip-Coated Lightguide modules also excludes electron data at 2 GeV/c and modules in APA1 for similar reasons as the Double-Shift modules. However, since the ARAPUCA module was in a prime location relative to beam, the 2GeV/c data was kept. Furthermore, the calorimetric energy reconstruction from scintillation light signals such as these will be further discussed in Section ??.

Efficiency

The photon detection efficiency was evaluated through 8 independent measurements using muon data and electron data at four different beam momenta, for each element of the PDS (12 cells in one ARAPUCA module, 10 Double-Shift Lightguide modules and 9 Dip-Coated Lightguide modules of the PDS beam side). Lightguide modules were not used, as to avoid any low statistics from the far-end of the beam, and possibly corrupting the average efficiency determination. By comparing
Figure 7.20: Electron events with 2 to 7 GeV/c were considered for the Dip-Coated (left panel) and ARAPUCA (right panel) modules efficiency results shown. The Dip-Coated Lightguide modules also excludes electron data at 2 GeV/c and modules in APA1 for similar reasons as the Double-Shift modules. However, since the ARAPUCA module was in a prime location relative to beam, the 2GeVc data was kept [44].

The results, efficiency estimated from the electron data was found in all elements systematically higher than from the muon data, regardless of the energy of the particle (see figures 7.17, 7.18 and 7.20).

The systematic difference may be due to bias in the MC simulation at the photon emission stage (e.g., an unaccounted deviation in scintillation yield for GeV-scale electrons and muons with respect to minimum-ionizing particles) and at the propagation stage (e.g., a difference due to the computational method used to approximate the number of photons reaching the PD optical window from localized volumes (EM showers) and long tracks (muons)). The mean value from all available measurements \( \langle \epsilon_j \rangle \) for the \( j \)-th element is taken as the best estimate of the efficiency of that element, and the standard deviation \( s_j \) that measures the dispersion around the mean is taken as an estimate of the systematic uncertainty on the efficiency. The statistical uncertainty, evaluated from the standard errors of the mean numbers of detected and incident photons in the data and MC samples of muons and electrons at different energies, is negligible.

Comparing modules or cells of the same type, relative variations in efficiency are within \( \pm 6\% \) for the ARAPUCA cells, \( \pm 20\% \) for the Double-Shift modules and greater than \( \pm 25\% \) for the Dip-
Table 7.5: Efficiencies of the detector technologies in the ProtoDUNE-SP Photon Detector System: median value among detectors of the same type, determined from the average of independent measurements with beam muons and electrons at different energies. The error is from systematic uncertainty, with negligible statistical uncertainty. The number of detectors of different types examined correspond to the fraction of PDS elements in the beam side upstream (APAs 3 and 2), selected to determine the median efficiency reported in the efficiency column [44].

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARAPUCA</td>
<td>$\tilde{\epsilon}_A = (2.00 \pm 0.25) %$</td>
</tr>
<tr>
<td>ARAPUCA (double area)</td>
<td>$\tilde{\epsilon}_{A2} = (1.06 \pm 0.09) %$</td>
</tr>
<tr>
<td>Double-Shift module</td>
<td>$\tilde{\epsilon}_{DS} = (0.21 \pm 0.03) %$</td>
</tr>
<tr>
<td>Dip-Coated module</td>
<td>$\tilde{\epsilon}_{DC} = (0.08 \pm 0.02) %$</td>
</tr>
</tbody>
</table>

Coated modules. The median efficiency value with its statistical and systematic uncertainty from each group of detectors ($\tilde{\epsilon}_A$, $\tilde{\epsilon}_{A2}$, $\tilde{\epsilon}_{DS}$, $\tilde{\epsilon}_{DC}$) is selected to characterize the different technologies implemented in the ProtoDUNE-SP Photon Detection System. These values are shown in Table 7.5. The overall relative uncertainty on the efficiency for all detector types is thus found to be $8.5% \leq \sigma_{\epsilon}/\epsilon \leq 13.5\%$, as determined from the set of measurements described above. This appears compatible with the systematic error expected from uncertainty in the parameters of the photon emission and propagation used in the MC generation.

7.5.3 Simulation Comparison using Cosmic Ray Muons

The analysis of photon signals from cosmic ray muons provides a check on the validity of the photon simulation used to determine efficiency. Throughgoing cosmic ray muons, or those which enter through the upstream face and exit through the downstream face of the cryostat, are isolated in the scintillation medium using CRT triggered events that have been matched to reconstructed tracks in the TPC. A trigger from this sub-detector involves a four-fold coincidence of the $x$- and $y$-
Figure 7.21: The left-hand panel shows the ratio of the observed to the predicted PE yields as a function of transverse distance, assuming two different values of the Rayleigh scattering length in the simulation. The data agree more with simulation that employs a Rayleigh scattering length ($L_R$) of 90 cm as opposed to the 60 cm prediction. On the right, an event-by-event comparison is shown with a simulated Rayleigh scattering length of 90 cm. The dashed vertical lines in both plots represents where data and simulation agree. The solid vertical lines in the right-hand plot show the same bounds of the plot on the left [44].

measuring planes of the CRT over the span of 60 ns producing events that are very likely to contain a throughgoing cosmic ray muon. Two strategies were employed, both using an event definition described by the sum of all detected photons in the twelve cells of the non-beam side ARAPUCA module during a $13.33 \mu$s externally tagged PDS trigger. Before either analysis, the sum of photons per event collected at the detector surface in the simulation were scaled by a fixed amount in order to eliminate a systematic normalization difference with data.

The first analysis, a comparison of the average light response as a function of transverse distance, was employed to observe some of the bulk effects of the medium. Here, the transverse distance
is defined as the length of the segment between the reconstructed particle path and the center point of the ARAPUCA module as they occupy the same position along the \( z \) axis. Since the ARAPUCA module is in the central APA (APA6), this variable is exclusively a function of the particle position in \( x \) and \( y \) as it bisects the detector in the \( z \) direction, exploiting the symmetry of the detector. The results of this analysis, shown in the left plot of Figure 7.21, suggest that the measured data favor simulation with Rayleigh scattering length hypothesis of 90 cm as opposed to a Rayleigh scattering length of 60 cm in the scintillation medium. A second analysis compares each data track to a simulated track generated with matching position and trajectory in a medium with Rayleigh scattering length set at 90 cm. In total, roughly 43,000 events taken over four months with a simulated event was compared. Results, which are shown in the right-hand plot of Figure 7.21, demonstrate excellent agreement with simulation as a function of the transverse distance from the ARAPUCA to the reconstructed track. In comparisons of data to simulation, one standard deviation in the difference between the reconstructed simulated light and the measured reconstructed light is about 18.6%. These two comparisons show that photons are successfully reconstructed in ProtoDUNE-SP and that the simulation of the optical properties of scintillation medium is in a good agreement with the measurements.

### 7.5.4 PDS Time resolution

The timing performance of the PDS intrinsically depends upon a combination of factors, from the intrinsic time resolution of the photosensor, to the electronics response of the readout board and signal digitization, to the features of the light propagation, wave-length shifting and photon collection by the PD modules. The overall timing performance is evaluated here in two different applications: time resolution of two consecutive light signals and time matching between light signal and TPC signal.

Resolving successive light signals in time is of importance in physics reconstruction of correlated
events, such as stopping muon with decay to Michel electron, or kaon decays, or nucleus de-excitation into gammas after neutrino interaction. Some of these correlations may be observed with light signals in LAr depending on the PDS timing performance. To explore this, data was taken with an external trigger using the DCM, producing two consecutive LED flashes with a fixed time difference among them and from the common trigger time. The time difference between the pulses was set in the few $\mu$s range typical of the muon decay at rest, and much larger than the pulse width. In Figure 7.22 (left) a recorded waveform from the DCM trigger is shown with the two generated consecutive LED pulses as detected by a PDS module and digitized by the SSP readout board. The rise time of each of the two signals from the common trigger was measured in the events collected with the DCM trigger and the distribution of their time difference $\Delta t = (t_2 - t_1)$ is shown in Figure 7.22 (right). The time resolution to observe two separate light pulses is $\sigma_{\Delta t} \approx 14$ ns. Time jitter in the DCM pulse formation is small (sub-ns range) and the dominant factor is from digitization (6.67 ns sampling period).

An efficient light flash-to-track matching in LArTPC is important for a correct event reconstruction, background rejection (especially for LArTPC’s operated on the surface) and low-energy underground physics. An average of approximately 70 cosmic ray tracks are observed overlaying
Figure 7.23: PDS Timing Measurements: Correlation between the TPC track $t_0$ time and the PDS flash time. Non-matched tracks (red points) are mostly from CPA-crossing vertical muons (large negative $t_0$) whose flash was not recorded by the PDS at the opposite end of the drift distance [44].

each beam event during TPC readout window. The cosmic ray tracks arrive at random times relative to the beam trigger. For some of these tracks, such as those that cross the cathode plane or cross one of the anode planes, their actual time of entering the LArTPC volume ($t_0$ time) can be reconstructed offline from the TPC data by using the 3D track reconstruction algorithms and the geometrical features of these CPA or APA crossing tracks. With the ProtoDUNE-SP TPC at its nominal electric field of 500 V/cm, the full drift time is 2.2 ms. Additional 2.25 ms (0.55 ms) are also recorded (before and after) the drift time period, for a total of 5 ms TPC readout window per recorded event. Cathode or anode crossing muons have $t_0$ time distributed over the entire recorded window and reconstructed with a precision of about 20 $\mu$s.

PDS detected light flashes corresponding to the $t_0$-determined TPC tracks are efficiently found in the packets received from the SSP and contained in the PD fragment of the event. Matching is performed in time inside the TPC readout range, looking for the closest flash timestamp to the $t_0$ time of the track, within a given coincidence window. In the case of CPA/APA-crossing tracks the matching efficiency depends on the SSP discriminator threshold for the packet recording and to the
width of the coincidence window. An example of flash-to-track matching is given in Figure 7.23, showing the bisector correlation of PDS flash time and TPC track \( t_0 \) time, for a 4500 APA/CPA crossing track sample. Tracks not matched to a flash are mostly the shorter CPA-crossing tracks whose flash was below threshold.

### 7.6 Energy Reconstruction & Resolution from Scintillation Light

Homogeneous calorimeters are instrumented targets where the kinetic energy \((E)\) of incident particles is absorbed and transformed into a detectable signal. The deposited energy is typically detected in the form of charge or light. When the energy is large enough, a shower of secondary particles is produced (through electromagnetic or strong processes) with progressively reduced energy. If the shower is fully contained and the output signal is efficiently collected, the calorimetric energy resolution is expected to be good, improving with energy as \(1/\sqrt{E}\). Calorimeters can also provide information on shower position, direction and size as well as arrival time \( t_0 \) of the particle.

A LArTPC is a sophisticated version of a homogeneous calorimeter, with additional imaging and PID capabilities, as described in Section 7.2.2. Energy deposition in the liquid argon target yields free charge from ionization, as well as yields fast scintillation light. The best energy resolution is obtained by collecting both the charge and light signals, which are anti-correlated by the randomness of the recombination processes. With detectors based on LArTPC technology, calorimetry typically relies only on the charge signal collection, while the use of the light signal is limited to \( t_0 \) determination and triggering purposes. A first attempt to extend the use of scintillation light for calorimetry was recently performed in the LArIAT experiment [101], using a low energy range in a small sized LArTPC. ProtoDUNE-SP’s charged particle test beam offered the opportunity to directly probe the calorimetric response of fully contained EM and hadronic showers in the sub- to few-GeV energy range, using scintillation light.

As described in Section 5.3, ProtoDUNE-SP’s PDS comprises of a series of PDS modules po-
Figure 7.24: This figure shows a 3D event display of a real 7 GeV beam electron in the TPC volume (only tracks inside a predefined sub-volume (red box) are shown). The beam electron enters near the cathode and an EM shower develops in LAr along the beam direction, about $10^\circ$ downward and $11^\circ$ toward the anode plane, where the PDS beam side modules are located inside the APA frames. Scintillation photons from energy deposits along the shower are detected by the ARAPUCA module [44].

Scintillation photons from energy deposits along the shower are detected by the ARAPUCA module [44].

The beam electron enters near the cathode and an EM shower develops in LAr along the beam direction, about $10^\circ$ downward and $11^\circ$ toward the anode plane, where the PDS beam side modules are located inside the APA frames. Scintillation photons from energy deposits along the shower are detected by the ARAPUCA module [44]. The active LAr volume is only on one side of the APA’s, on the side facing the central cathode. The total photo-sensitive area is $\sim 1.5\%$ of the boundary surface of the LAr volume. The relatively modest optical coverage and the one-sided geometry of the PDS at ProtoDUNE-SP, compared for example to the $4\pi$ coverage of scintillation or Cherenkov detectors ($\sim 20 - 40\%$), are expected to limit the light yield and the uniformity of the calorimetric response along the drift direction. In this section, beam electrons and data from the (beam-facing side) ARAPUCA module are utilized to investigate the light yield and resolution of the ProtoDUNE-SP Photon Detection System.
7.6.1 Beam electrons and EM showers

In a sequence of beam runs, data were collected with incident positive electrons ($e^+$) with energies of 0.3, 0.5, 1, 2, 3, 6 and 7 GeV, providing a large sample of EM showers developing in the LAr volume. The beam is delivered with a typical momentum spread of ±5% around the nominal setting. The beam line instrumentation (see section 5.2.1 and 7.2.2) provides an event-by-event PID and momentum measurement with a precision of $\Delta p/p \simeq 2.5\%$ [68]. Light signal from the single beam-facing side ARAPUCA module is used for this calorimetric response study. The ARAPUCA module is positioned inside the upstream APA3 frame, nearly at the same height $y$ of the entering beam and oriented along the $z$ axis. In Figure 7.24 a 3D display of a 7 GeV electron event from the ProtoDUNE-SP data sample is shown as reconstructed by the TPC. The EM shower develops immediately downstream of the beam entry point in the LArTPC volume in front of the ARAPUCA module, at $\sim$3 m distance in the $x$ (drift) direction, and propagates longitudinally along the beam direction, about $10^\circ$ downward and $11^\circ$ toward the anode plane. Scintillation light is emitted isotropically from every location at which ionization occurs along the shower.

The total photo-sensitive area of the ARAPUCA module is $\sim 0.5 \times 10^{-3}$ of the surface surrounding the LArTPC active volume (beam side). Summing over the twelve cells in the ARAPUCA module, the total number of photons detected $N_{Ph} = \sum N_{Det}$ is evaluated event by event, for each beam run. Monte Carlo events, already used for the efficiency study, are also available, generated as described in Section 7.5.2 with incident electrons as in the beam runs (same energy distributions and direction). Scintillation light from the EM shower development in LAr is propagated to the photon detectors and the total number of photons incident on the surface of the ARAPUCA module is evaluated for each event of the MC simulated momentum run.

Figure 7.25 shows the energy distribution (left) of the incident electrons from the beam spectrometer of ProtoDUNE-SP’s beam line for each beam run and the corresponding calorimetric response from the ARAPUCA detector module (right), expressed by the number of detected pho-
Figure 7.25: Distributions of the incident beam electron energies (left) and corresponding detected photon spectra (right) for the collected seven nominal beam energies (Gaussian fit superimposed). The photon spectra are relative to the sum of photons detected by the 12 cells of the ARAPUCA PDS module [44].
tons. A Gaussian fit of both distributions (red lines in Figure 7.25) gives the average electron energy \( \langle E_e \rangle \) and the corresponding average photon counting \( \langle N_{ph} \rangle \), and their spreads \( \sigma_E, \sigma_N \), for each run. The average number of detected photons as a function of the beam energy is shown in Figure 7.26. This relationship gives the calorimetric energy response from the light-detection side. Correspondingly, the response as obtained from the MC simulation, expressed by the average number of detectable photons (incident at the detector surface) from EM showers at given electron beam energy, is presented in Figure 7.27 (left).

To a first approximation, the average light response is a linear function of the energy over the entire range of tested beam energies, as shown in Figure 7.26 (left). The slope of the fit \( p_1 \) gives the light yield \( Y_{\text{light}} = 102.1 \) photons/GeV. The quoted \( Y_{\text{light}} \) is relative to a diffuse light source (EM shower) at a distance of about 3 m (see Figure 7.24). The non-zero (negative) intercept \( p_0 = -8.4 \) photons from the fit) corresponds to an incident energy offset of \( -82 \pm 14 \) MeV from the nominal value for all beam energies. From the ProtoDUNE-SP beam line MC simulations [44] beam electrons are expected to release 10-20 MeV in the material in the portion of the beam line downstream of the spectrometer and an additional \( \sim 20-30 \) MeV while crossing the materials inside the cryostat from the end of the beam pipe and the active volume of the TPC (cryostat insulation and membrane, beam tube and a thin LAr layer in between). The observed energy offset from the linear fit of the light response provides direct evidence, though in slight excess, of the expected energy loss of beam electrons before entering the LArTPC. A slight deviation from linearity is observed in the light response at higher incident energies, both in the data (Figure 7.26 - left) and in the Monte Carlo (Figure 7.27 - left). This is due to the light response dependence on source-to-detector distance.

At higher energies, the longitudinal shower profile extends deeper in the LAr volume along the beam direction and closer to the ARAPUCA module, with some increase of visibility. Based on the reconstruction of the shower profile at the different incident electron energies (see Figure 7.20 - right), a geometry correction to the cells’ acceptance has been calculated and a normalization
factor applied to the data at different energies. Most of the nonlinearity was then removed. The intercept of the linear fit after correction indicates an energy offset of $-56 \pm 14$ MeV, in better agreement with the expected beam electron energy loss in the materials before entering the TPC.

Based on the linearity of the light response, the relative calorimetric energy resolution $\sigma_E/E_e$ is obtained from the $\sigma_N/N_{Ph}$ ratio of the light response (Figure 7.26 - right). The energy resolution, as for a homogeneous calorimeter, can be expressed in a general form [102] depending on three different contributions:

$$\frac{\sigma_E}{E} = k_0 \oplus \frac{k_1}{\sqrt{E}} \oplus \frac{k_2}{E}$$  \hspace{1cm} (7.4)

where the symbol $\oplus$ indicates a quadratic sum and $E$ is in GeV. The terms on the right-hand side are referred to below as the constant term, the stochastic term, and the noise term, respectively.

The relative weight of the three terms depends on the energy of the incident particle.

The stochastic term ($k_1$) contribution to the energy resolution comes from the statistical fluctuations in the number of photons detected. The relatively large value of 9.9 %, shown by the fit
in Figure 7.26 - right, when compared to typical homogeneous calorimeters, is attributed to the limited photo-sensitive coverage of the ARAPUCA module.

The noise term $(k_2)$ comes from the electronic noise of the readout chain. Its value of 0.057 GeV is exactly as expected from the measured signal-to-noise-ratio of the ARAPUCA readout (Section 7.4.3).

The constant term $(k_0)$ is large (6.2 \%) and due to different contributions. The main contribution comes from the incident beam electron energy spread, shown in Figure 7.25 - left, depending on the actual beam line configuration (collimators aperture at different momentum setting). An additional contribution comes from fluctuations in the energy loss in the materials before electrons enter the TPC. Since the energy loss occurs downstream of the momentum spectrometer, this energy degradation and its fluctuation do not appear in the incident beam energy spectra and it is evaluated by simulations ($\sim$ 2\%). Other contributions to the resolution, such as non-uniformity on the detector illumination, channel to channel response variation and possible shower leakage across the cathode, have been investigated and shown to be negligible.
Given the determination of the constant term, stochastic term, and noise term, the energy resolution \( \sigma_E/E_e \) is thus determined (using eq. 7.4) to be \( 5.8 \pm 0.4 \% \). This is an excellent calorimetric response to beam electrons light signals in ProtoDUNE-SP.

A comparison of electron data and the corresponding MC simulation can be used to validate the simulation of the light propagation and collection. The average number of photons incident on the surface of the ARAPUCA module from the MC (shown in Figure 7.27 - left) is scaled by a normalization factor \( \eta \), an average value over the ARAPUCA cells’ efficiency shown in Section 7.5.2, to give the simulated detected photons \( \langle N_{Ph} \rangle_{\text{simulated}} = \eta \langle N_{Ph} \rangle_{\text{incident}} \). The ratio \( \langle N_{Ph} \rangle_{\text{detected}}/\langle N_{Ph} \rangle_{\text{simulated}} \) is shown as a function of incident beam energy in Figure 7.27 (right). A systematic deviation, between 5 and \( \leq 10\% \), is found for electrons with energies between 0.3 GeV and 1 GeV. This deviation is attributed to the statistical limitations on the visibility values of the photon library used in the Monte Carlo for converting the energy deposited along the EM shower into the number of photons impinging upon the ARAPUCA module.

### 7.7 PDS Analysis Summary

Sections 7.4, 7.5, and 7.6 has described how we characterized our photosensors/photon detectors, how we defined and calculated the performance, and how we used scintillation light for energy reconstruction and resolution.

The PDS ARAPUCA module was shown to have an excellent calorimetric response to beam electron light signals in ProtoDUNE-SP, as well as linearity over the entire range of energies analyzed. Despite its relative small photo-sensitive area and the large distance from the light source (\( \sim 3\,m \)), an excellent calorimetric response has been observed.

This performance can be extrapolated further. By scaling this calorimetric response, we can calculate an expected light yield for the DUNE Far Detector Horizontal Drift. Considering a ProtoDUNE-SP experiment consisting entirely of ARAPUCA modules, we can scale the efficiency
response (Section 7.5.2) using the ratio of ARAPUCA-to-Lightguide module efficiencies. The result of this indicates an expected light yield of 1.9 photons/MeV. This performance exceeds the specifications required for the DUNE Far Detector [103].
Chapter 8

Conclusion and Outlook

Liquid Argon Time Projection Chambers are ideal for studying neutrino oscillation physics, supernovae neutrino observations, and searches for nucleon decay. The DUNE experiment with its main components—Neutrino Beam, Near Detector, and Far Detector—is based on this technique and aims to achieve these scientific goals. The high sensitivity of DUNE will contribute to our understanding of the yet unknown factors responsible for the matter-dominated universe we live in. To build massive next-generation experiments such as DUNE, bold efforts are necessary to pave the way for large-scale LArTPC detectors.

The operation of the ProtoDUNE-SP detector was extremely successful and vital for our DUNE progress. The detector successfully operated for multiple years, validating key design choices intended for the DUNE Far Detector, as well as enabling detailed studies of various particle cross sections and scintillation light production and propagation in liquid argon. I was fortunate to be a core member of the selected group in building, commissioning, and running the ProtoDUNE-SP detector. I became one of the main experts on the Photon Detection System, as well the ground lead for the installation, commissioning, and operations. During the beam-time period, I was the on-call expert for the Photon Detection System. Additionally, I provided essential contributions to the overall data-taking campaign, including training new shifters and assuring the collection of high-quality data.

This thesis comprehensively reports on the light yield and resolution response obtained by all three Photon Detection System technologies at ProtoDUNE-SP. Most notably, (1) the characterization and response to muon and electron beam particles over a range of beam momenta, from 0.3 GeV/c - 7 GeV/c; (2) the use of scintillation light for energy reconstruction and resolution; (3) performance indicating an expected light yield of 1.9 photons/MeV for the DUNE Far Detector.
Horizontal Drift, exceeding the specifications required for DUNE.

The experience and overall validation of the leading technology options at ProtoDUNE-SP has been invaluable toward the progress of scintillation light detection for DUNE. This progress of understanding the physical properties and response of these detectors will contribute to the sensitivity measurements required for determining $t_0$, ultimately contributing to the success of the sensitivity measurements required for determining the neutrino mass hierarchy and $\delta_{CP}$.

I have made major contributions to the development of the Photon Detection System for DUNE, and in the establishment of procedures for commissioning and integration of the Photon Detection System that will be valuable during the construction, installation, and operation of the DUNE Far Detector. Thanks to my extensive involvement in ProtoDUNE-SP, I was one of a small number of collaborators selected for writing sections of lengthy journal articles, detailing our work and analysis regarding the Photon Detection System [44, 26, 104].

8.1 Onward with PDS Development in DUNE

The many lessons learned from the ProtoDUNE-SP PDS development (Chapter 4), integration (Chapter 6), and analysis (Chapter 7) have been essential for the continued progress of DUNE. DUNE’s Far Detector has moved forward for both Horizontal Drift (Section 2.5.1) and Vertical Drift module (Section 2.5.2) with the X-ARAPUCA technology as its photon detector design of choice.

The X-ARAPUCA design is effectively a hybrid between the ARAPUCA (Section 5.3.3) and the Double-Shift Lightguide (Section 5.3.2) designs implemented in ProtoDUNE-SP [25]. Figure 8.1 shows a cartoon of the design, displaying the assembled cell (left) and the exploded cell view (right). The yellow plates represent the dichroic filters, which are coated on their outside surfaces with p-terphenyl (PTP) as its WLS. The pale blue plate represents the WLS plate (similar to the Double-Shift’s inner lightguide), and the photosensors are visible on the right side of the cell.
Figure 8.1: This figure shows a 3D schematic depiction of a X-ARAPUCA cell design. Left: assembled cell. Right: exploded view. The yellow plates represent the dichroic filters (coated on their outside surfaces with p-terphenyl (PTP) WLS), the pale blue plate represents the wavelength shifting plate, and the photosensors are visible on the right side of the cell [25].

This new and improved PDS detector is already being tested. Similar to the coldbox testing done for ProtoDUNE-SP (Section 6.2.4), the X-ARAPUCA is being tested for the next ProtoDUNE-II experiment, set to begin sometime in 2023. The current setup for this experiment is very similar to ProtoDUNE-SP, but with upgrades to the Anode Plane Assemblies (APAs), Cold Electronics (CEs), and PDS (all with X-ARAPUCA modules). Further, the X-ARAPUCA has already been incorporated into the Vertical Drift (VD) detector design. The main difference here being that the photon detectors will be implemented within the cathode instead of the anode, as well as all around the field cage and end walls (see Section 2.5.2). Similar to ProtoDUNE-SP, there will be a ProtoDUNE-VD (also located at the CERN Neutrino Platform) in order to test the main components for this detector design, which is expected to be tested between 2023 - 2024. Current full-scale tests have already begun for the Vertical Drift. Figure 8.2 shows an installed X-ARAPUCA module (made up of many X-ARAPUCA cells) within the VD cathode module inside of the NP02 coldbox, located at the CERN Neutrino Platform.
Figure 8.2: This figure shows an installed X-ARAPUCA module (made up of many X-ARAPUCA cells) within the VD cathode module inside of the NP02 coldbox, located at the CERN Neutrino Platform
Table 8.1: This table shows the breaking down the PDS detectors determined efficiency in ProtoDUNE-SP, if we were to consider their relative efficiency ($\tilde{\epsilon}$) and number of photosensors ($S$), per active area ($A$).

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>$\tilde{\epsilon} \text{ [%]}$</th>
<th>$A \text{ cm}^2$</th>
<th>$S$</th>
<th>$\tilde{\epsilon}/S/A \times 10^{-6} \text{ [%]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARAPUCA</td>
<td>$\tilde{\epsilon}_A = (2.00 \pm 0.25)$</td>
<td>1238.72</td>
<td>192</td>
<td>$(8.41 \pm 1.05)$</td>
</tr>
<tr>
<td>ARAPUCA (double area)</td>
<td>$\tilde{\epsilon}_{A2} = (1.06 \pm 0.09)$</td>
<td>1238.72</td>
<td>96</td>
<td>$(8.91 \pm 0.76)$</td>
</tr>
<tr>
<td>Double-Shift module</td>
<td>$\tilde{\epsilon}_{DS} = (0.21 \pm 0.03)$</td>
<td>1646.61</td>
<td>12</td>
<td>$(10.63 \pm 1.52)$</td>
</tr>
<tr>
<td>Dip-Coated module</td>
<td>$\tilde{\epsilon}_{DC} = (0.08 \pm 0.02)$</td>
<td>1732.84</td>
<td>12</td>
<td>$(3.85 \pm 0.96)$</td>
</tr>
</tbody>
</table>

8.2 Future Light Detector development

For many reasons, DUNE has proceeded with the (X-)ARAPUCA technology advancement for its future LAr Photon Detectors, as just described (Section 8.1). The efficiency shown by the ARAPUCA module in ProtoDUNE-SP did yield best performance results (Section 7.5.2). However, we could further consider the possibility of modifying all detectors, not just the ARAPUCA for advancements. Further, I would claim that the advancement for the Double-Shift Lightguide technology (developed at IU) could be a serious candidate moving forward for future LAr light detectors.

Table 8.1 shows if we were to consider the efficiency of each PDS photon detector determined at ProtoDUNE-SP, but now including the given active area and number of photosensors each module used. Considering the relative information, it is clear that the number of photosensors for a given module drastically changes the outcome of the overall efficiency. That being said, it is not so clear when you consider each efficiency calculation, as it does not have the same active area dimensions of one another. Therefore, one method would be to consider breaking down the efficiency, per photosensor, per active area, as shown in the far right of Table 8.1. From this, it is clear that the Double-Shift Lightguide technology is comparable to the ARAPUCA technology.
Continuing forward, the Double-Shift Lightguide design is more simplistic than the ARAPUCA design, at the mechanical level. In regards to DUNE, the Far detector Horizontal Drift alone will need approximately 1,500 PDS modules for each of the four 10kt module (10 PDS modules per APA \times 150 APAs per 10kt). Considering the integration, transport, and the collaborative support of handling the detectors, the PDS design moving forward must be robust. In my opinion, the Double-Shift Lightguide is robust and easily reproducible, at the industrial level—something the ARAPUCA design is still developing. As a quick comparison with the Dip-Coated technology vs. the Double-Shift technology, it is clear from the table that the Double-Shift yields better results. In addition, the complexity of the dipping mechanism used for the Dip-Coated technology is (in my opinion) not easily reproducible.

In all cases, both the ARAPUCA and Double-Shift Lightguide technologies are novel LAr photon detector designs. However, I could realistically imagine the possibility of establishing a promising research and development proposal, in order to further develop the Double-Shift Lightguide technology. With the many lessons learned from our work done at IU, Fermilab, and at CERN, there is serious potential in the Double-Shift Lightguide becoming a robust and efficient photon detector for future LAr experiments.
Appendix A

Passive Ganging Studies-APPENDIX

As discussed in 4.1.1, one of the main constraints of the PDS is to minimize cost, while maximizing light detection efficiency for DUNE-SP. Therefore, reducing costs with minimum effects is ideal. One sensible way to reduce costs is through reducing channel readout for the PDS detector modules. Testbed experiments were made locally at IU on the performance of passively ganging channels—connecting signals in parallel—in order to reduce channel count and therefore, reduce total electronic costs. A detailed description of the performance of passively ganging 3 and 6 SiPMs relative to a single SiPM readout is discussed in technical doc [56] and will be discussed briefly here.

Detecting single-photon scintillation signals are vital for low energy resolution, as discussed in Chapter 3.2.2. In addition, SiPM dark rates are on the order of 10Hz at LAr temperatures. Therefore, to test low level signals, without introducing scintillation light, using \( \sim \) LAr temperatures, liquid nitrogen (LN2) was used instead of LAr to keep electronics cold, being there is only a minor difference in evaporation temperature (87K vs 77K, respectively). Running the experiment for several minutes results in collecting a sufficient amount of signals for an analysis of low level signal pulses (1 or 2 PE).

In addition to these ganging studies, the effects on signal by varying cable lengths, using Gore shielded-twisted pair cables and the difference between signal response in cryogenic and room temperature was inspected.

Experimental Methods

Figure A.1 shows the electronics board, containing 3 individual SiPMs, a passive gang of 3 and 6 SiPMs. The electronics board was attached to a plastic lid, via metal rods, and suspended in a small dewar containing liquid nitrogen (LN2), as shown in Figure A.2. To run dark measurements, the
Figure A.1: This Figure shows the electronics board used for our passive ganging studies. Starting from the left, three individual SiPMs used as reference to study a passively gang of 3 and a passively gang of 6 SiPMs.

dewar was placed inside a light-tight dark box, transmitting the SiPM signals outside through a feed-through via Gore shielded twisted pair cables. The outside cables (10 m, 20 m, 40 m) transmitted the dark signals to an SSP for digitization and processing. In addition, the outside cables were tested both in room and LN2 temperature. For cold cable measurements, the outside readout cables were submerged in LN2, via insulating box.
Figure A.2: This figure shows the setup used in the IU testbed passive ganging experiment. The dewar, containing the different passively ganging schemes shown on the right, was placed inside a light-tight dark box, transmitting the SiPM signals outside through a feed-through, via Gore shielded twisted pair cables, to an SSP for digitization and processing.
<table>
<thead>
<tr>
<th>SiPM</th>
<th>ADC/PE</th>
<th>Rise</th>
<th>Decay</th>
<th>Rise</th>
<th>Decay</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ns]</td>
<td>[ns]</td>
<td>[ns]</td>
<td>[ns]</td>
<td>[ns]</td>
<td>[ADC]</td>
</tr>
<tr>
<td>Average Individual</td>
<td>20.3</td>
<td>13.4 ± 0.5</td>
<td>473</td>
<td>12.8 ± 0.7</td>
<td>468</td>
<td>2.45 ± 0.30</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>9.5</td>
<td>19.0 ± 0.6</td>
<td>892</td>
<td>16.2 ± 0.6</td>
<td>863</td>
<td>2.51 ± 0.18</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>5.3</td>
<td>-</td>
<td>-</td>
<td>19.9 ± 1.0</td>
<td>1317</td>
<td>2.53 ± 0.18</td>
</tr>
</tbody>
</table>

Table A.1: Mean Waveform Parameters for 10m Cables

Analysis

Signals are very similar to that of Figure 4.1, however, when increasing the amount of SiPMs ganged together, the shape characteristics alters due to capacitance and charge conservation within each signal. As discussed in section 4.1.2, the SSP provides the voltage necessary to bias the SiPM (or set of SiPMs), as well as digitizing, triggering, and processing signals, allowing us to optimize our results.

The SSP’s peakSum variable calculates the sum of samples near the peak of waveform and is used to separate waveforms by photoelectrons (PE). Plotting this variable for all collected waveforms allows us to see baseline triggers (0PE) and signal pulses (1PE, 2PE, ...etc). A Gaussian is fitted to the desired PE region to the peak bin distribution, ±2 ADC. This is shown in Figure A.3.

A second scan of the waveforms are collected, that fall within one sigma of this Gaussian-fit distribution and is averaged and smoothened, using a 5-sample running average. Properties, such as waveform baseline, amplitude, rise/fall time, and ADC/PE are then determined and compared. Figures A.4, A.5, and A.6 show an example of a typical averaged waveform for each ganging scheme.

Tables A.1-A.3 are tests done with cables at room temperature. All rise and decay times for individual and gang of 3 SiPMs were calculated for 1PE and 2PE. For the gang of 6 SiPMs only 2PE was used since 1PE was buried in the baseline noise. The tables show that the rise time, decay time and ADC/PE are strongly correlated with the number of SiPMs passively ganged together- as
Figure A.3: This is an example plot of the SSP’s peakSum variable for all collected waveforms from triggers and pulses for a single run, with a Gaussian fit over a 1PE region (Peak ±2 ADC).

Figure A.4: This is an example of an averaged 1PE waveform, with 10m cable, showing the line from which the rise time was determined (red), the falling edge fit used to determine the decay time (red), and the determined amplitude (in green).
Figure A.5: This is an average 1PE waveform, with 10m cable, for a passive gang of 3. Notice that the ADC/PE has dropped by about a factor 2 when compared to an individual SiPM and that the rise and decay time has increased.

Figure A.6: This is an average 2PE waveform, with 10m cable, for a passive gang of 6 SiPMs (1PE is buried in the baseline noise). We can see that the ADC/PE has dropped again by about a factor of 2 with respect to Figure A.5, with the rise and decay time further increasing.
<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Average Individual</td>
<td>19.5</td>
<td>14.7 ± 0.5</td>
<td>479</td>
<td>14.8 ± 0.7</td>
<td>483</td>
<td>2.50 ± 0.30</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>9.4</td>
<td>22.9 ± 0.9</td>
<td>868</td>
<td>18.9 ± 0.8</td>
<td>874</td>
<td>2.50 ± 0.19</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>5.2</td>
<td>-</td>
<td>-</td>
<td>23.4 ± 1.4</td>
<td>1282</td>
<td>2.55 ± 0.20</td>
</tr>
</tbody>
</table>

Table A.2: Mean Waveform Parameters for 20m Cables

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Average Individual</td>
<td>17.9</td>
<td>18.6 ± 1.1</td>
<td>490</td>
<td>14.7 ± 0.9</td>
<td>482</td>
<td>2.55 ± 0.40</td>
</tr>
<tr>
<td>Gang of 3 SiPM</td>
<td>8.6</td>
<td>27.1 ± 2.1</td>
<td>877</td>
<td>20.3 ± 1.4</td>
<td>866</td>
<td>2.63 ± 0.29</td>
</tr>
<tr>
<td>Gang of 6 SiPM</td>
<td>4.8</td>
<td>-</td>
<td>-</td>
<td>23.5 ± 3.1</td>
<td>1233</td>
<td>2.67 ± 0.29</td>
</tr>
</tbody>
</table>

Table A.3: Mean Waveform Parameters for 40m Cables

the number of passively ganged SiPMs increase, both rise and decay times increase, while ADC/PE decreases. In addition, the outside cables that were tested both in room and LN2 temperature were found to be independent of temperature, but that cable length is positively correlated with baseline noise. Further discussion on this is found in the technical document [56].
Bibliography


[38] Patrick Huber, M. Lindner, and W. Winter. “Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)”. In: Comput.


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Curriculum Vitae

EDUCATION

Ph.D Astrophysics
Indiana University
December 2022

M.A. Astronomy
Indiana University
September 2018

B.S. Physics, Minor: Mathematics
California State Polytechnic University, Pomona
June 2014

Research Interests

- Experimental Particle Physics: Neutrino Oscillations
- Instrumentation Development for Particle Physics: Photon Detection
- Scintillation Properties of Liquid Argon
- Integrated Systems, Detector Readout, Data Acquisition, and Monitoring
- Physics Education and Public Outreach

PROFESSIONAL SERVICE SKILLS

Postdoctoral Research Scholar
The University of Iowa
2021-Present

*DUNE Far Detector-2 Vertical Drift*

- Charge Readout Planes
- Cold Electronics
- Photon Detection System
- Installation/Commissioning/Operations

Fermilab/CERN
2016/2018-Present

Onsite Subsystem Lead for the Photon Detection System
*ProtoDUNE-Single Phase at CERN*
2018-2019

- Installation/Commissioning/Operations
- Photon Detector System Trainer
- On-call Expert
- DAQ Trainer/Shifter

Computer Languages Software

- Python
- C++
- PyROOT
- ROOT
- Bash
- LabVIEW
- GitHub
- LATEX
RESEARCH EXPERIENCE

Astrophysics Ph.D. Candidate, Indiana University  
*Thesis Advisor: Dr. Jon Urheim*  
2018-2022

Neutrino Hunting: Looking through a UV Lens  
Scintillation Photon Detection in a Large-Volume Liquid Argon Time Projection Chamber, Exposed to a Multi-GeV Charged Particle Beam

**Visiting Scientist, California Institute of Technology**  
*Local Advisor: Dr. Leon Mualem*  
2019-2020

Calibration and Efficiency Analyses for ProtoDUNE-Single Phase Photon Detection System. Includes Studies of Three Photon Detector Technologies, with a Focus on Electron-Beam Information.

**Research Assistant, Indiana University**  
*Advisor: Dr. Stuart Mufson*  
2017-2018

RD for DUNE Photon Detection Working Group, Working Testbeds at IU, Fermilab, and CERN. Focused on Photon Detector Deliverables, such as Readout Systems and QA/QC for the ProtoDUNE-Single Phase Photon Detection Production.

**REU Summer Student, University of Arizona**  
*California-Arizona Minority Partnership for Astronomy Research and Education Program*  
*Advisor: Dr. Josh Eisner*  
2013

Determined System Parameters of the GJ1214b Exoplanetary System. Created a Model Simulating an Exoplanet Transiting Across its Parent Star, Comparing Data taken by the Kuiper 61" Telescope, Arizona, to Determine its System Parameters.

MENTORSHIP PUBLIC OUTREACH

Graduate Research Mentor, Maria Manrique (Indiana University)  
2018-2020

Graduate Research Mentor, Erin Ewart (Indiana University)  
2019-2021

Undergraduate Research Supervisor, Thomas Rainbolt (Indiana University)  
2019-2021

Hosted public viewing at Kirkwood Observatory (Indiana University)  
2015-2018

Physics and Astronomy Open House Science Fest (Indiana University)  
2015-2018
TEACHING EXPERIENCE

**Associate Instructor, Indiana University**  
*A100-The Solar System/A105-Stars and Galaxies/A100-The Solar System Online Course*  
2015-2018

**Instructor, C2 Education**  
*Physics/Calculus/Chemistry/SAT ACT Math/Science*  
2014-2015

**Learning Assistant, Cal Poly Pomona**  
*Freshman Physics/Sophomore Physics*  
2013

**College Tutor, Cal Poly Pomona**  
*Physics/Calculus*  
2012-2013

**Differential Equations Grader, Cal Poly Pomona**  
*Physics/Calculus*  
2012

AWARDS

Joseph and Frances Morgan Swain Graduate Fellowship (Indiana University)  
2019

Frank and Margaret Edmondson Prize for Classroom Teaching (Indiana University)  
2018

Boeing Scholarship (Cal Poly Pomona)  
2014

PUBLICATIONS & TECHNICAL DOCUMENTS

Primary Publications

“Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC,”


“First results on ProtoDUNE-SP LArTPC performance from a test beam run at the CERN Neutrino Platform,”

B. Abi *et al.* (DUNE Collaboration), *JINST* 15 P12004 (2020)
“Differences in the response of two light guide technologies and two readout technologies after an exchange of liquid argon in the dewar,”


“A measurement of absolute efficiency of the ARAPUCA photon detector in Liquid Argon,”

D. Totani et al., *JINST* 15 T06003 (2020)

“A Novel Use of Light Guides and Wavelength Shifting Plates for the Detection of Scintillation Photons in Large Liquid Argon Detectors,”


**Collaboration Publications**

“Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment”


“Experiment Simulation Configurations Approximating DUNE TDR”

B. Abi et al. (DUNE Collaboration), arXiv:2103.04797 (2020)

“Long-baseline neutrino oscillation physics potential of the DUNE experiment”


“Volume IV. The DUNE far detector single-phase technology”

B. Abi et al. (DUNE Collaboration), *JINST* 15 T08010 (2020)

“Volume III. DUNE far detector technical coordination”

B. Abi et al. (DUNE Collaboration), *JINST* 15 T08009 (2020)


“Volume I. Introduction to DUNE”

B. Abi et al. (DUNE Collaboration), JINST 15 T08008 (2020)

“The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology and Strategies,”


“The DUNE Far Detector Interim Design Report, Volume 3: Dual-Phase Module,”


Technical Documents

“Photon Detection System Integration Information for ProtoDUNE,”

C. Macias, DUNE-doc-8618 (2018)

“PD Commissioning Activation Activities,”

C. Macias, DUNE-doc-8492 (2018)

“How To Make an Entire Cold Box PD Run @ProtoDUNE,”

C. Macias, DUNE-doc-7293 (2018)

“Tallbo Engineering Note,”


“Passive Ganging Studies,”

C. Macias, B. Howard, DUNE-doc-1464 (2016)
INVITED TALKS

“On the Path to Building the Largest Monolithic Liquid Argon Neutrino Detector, DUNE Invited Seminar at The University of Iowa ,”

C. Macias, DUNE-doc-25532 (2022)

“Photon Detection System for ProtoDUNE Single Phase, Light Detection In Noble Elements,”

C. Macias, DUNE-doc-15818 (2019)

“Toward Obliquity Measurements from Starspots in the GJ1214b Exo-planetary System, California-Arizona Minority Partnership for Astronomy Research and Education Symposium,”

C. Macias, Cal Poly Pomona (2013)

COLLABORATION PRESENTATIONS

“CRP1b evolution and status for DUNE Far Detector-2 Vertical Drift, DUNE Collaboration Meeting,”

C. Macias, DUNE-doc-25530 (2022)

“Status of CRP1B Testing - Hardware Configuration for DUNE Far Detector-2 Vertical Drift, DUNE Collaboration Meeting,”

C. Macias, DUNE-doc-25527 (2022)

“CRP-1 Inspections and Modifications for DUNE Far Detector-2 Vertical Drift, DUNE Collaboration Meeting,”

C. Macias, DUNE-doc-24488 (2022)

“Photon Detection System SensL Calibration for ProtoDUNE Single Phase, DUNE Collab-
oration Meeting,”

C. Macias, DUNE-doc-15673 (2019)

“Photon Detection System Operations Update for ProtoDUNE Single Phase, DUNE Collaboration Meeting,”

C. Macias, DUNE-doc-15670 (2019)

“Photon Detection System Status for ProtoDUNE Single Phase, DUNE Collaboration Meeting,”

C. Macias, DUNE-doc-8297 (2018)

“Toward Obliquity Measurements from Starspots in the GJ1214b Exo-planetary System, California-Arizona Minority Partnership for Astronomy Research and Education REU Talks,”

C. Macias, University of Arizona (2013)