



STUDIES ON THE SCINTILLATION LIGHT DETECTION IN THE PROTODUNE DUAL PHASE LIQUID-ARGON TPC AND ITS CAPABILITY FOR THE SUPERNOVA TRIGGER IN DUNE

Estudios sobre la detección de luz de centelleo en la TPC de argón líquido
ProtoDUNE Dual Phase y su capacidad para el disparo de supernovas en DUNE

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Introduction

The discoveries in neutrino physics achieved during the past half-century have had a deep impact not only on the Standard Model of particle physics but also on other fields such as astroparticle physics and cosmology. In particular, about twenty years ago, the observation of the neutrino oscillation mechanism that implies neutrinos have non-zero masses completely transformed the goals and prospects of neutrino experiments. Although they have the potential to answer several fundamental questions related to the nature of matter and the evolution of the universe, many of the neutrino properties still remain unknown and, thus, further research is necessary.

The Deep Underground Neutrino Experiment (DUNE) is a next-generation experiment for long-baseline neutrino oscillation measurements, neutrino astrophysics and proton decay searches. It aims at addressing key topics such as the CP violation phase measurement in the leptonic sector and the neutrino mass ordering determination. The physics program also includes the detection of the electron neutrino flux from a galactic core-collapse supernova. DUNE is a leading-edge project based on the international collaboration of over 1300 experts. The experiment will consist of a multi-purpose near detector (ND) located just downstream the powerful neutrino beam at Fermilab and a massive far detector (FD) 1.5 km underground at SURF, 1300 km away. Namely, DUNE FD will have four 17-kt mass liquid-argon (LAr) time-projection chamber (TPC) modules, complex particle detectors never built at such a large scale before.

The basic working principle of a LAr TPC is the collection of ionization charges produced by the interaction of a particle with the argon atoms. These charges drift thanks to an electric field until reaching the readout system. In addition, being argon an excellent scintillator, scintillation light signals are produced and detected as well, providing fundamental timing information for the track reconstruction and for triggering on non-beam events. Although the operation of a LAr TPC involves some technical challenges, the device provides 3D imaging, an excellent particle identification and an extraordinary energy resolution. The main LAr TPC technologies are the single-phase (SP), with the detector full of LAr, and the dual-phase (DP), in which both liquid and gaseous argon are employed.

In order to demonstrate the feasibility of the DUNE FD, an R&D program is currently underway at the CERN Neutrino Platform. In particular, ProtoDUNE Dual Phase, a DP LAr TPC with 300 t of active mass and 6 m of vertical drift, was operated with cosmic muons in 2019-2020 aiming to develop and validate the new features of the DP design for DUNE. It was the largest DP LAr TPC ever operated. The DP technology relies on a liquid argon volume with an upper layer of gas argon which allows the amplification of the signals. Despite its various advantages with respect to the SP mode (such as the

finer spatial resolution and the longer drift distances), the DP approach is more novel and challenging than the mature SP technology.

This thesis is mainly focused on the study of the performance of the ProtoDUNE-DP photon detection system (PDS), formed of 36 photomultiplier tubes (PMTs) placed on the cryostat floor. As the PMTs are not sensitive to the VUV scintillation light, two wavelength shifters (WLS) were deployed to convert the 127-nm light into visible photons: a PEN sheet on 30 PMTs and a TPB coating on 6 PMTs. ProtoDUNE-DP design counts on a dedicated light calibration system (LCS) to monitor the PMT response.

The first chapters of this dissertation will extend this introduction, as they will offer an overview of neutrino physics, the LAr TPC principles and the DUNE experiment. Then, the features of the different systems of ProtoDUNE-DP, focusing on the PDS and the LCS, will be commented. The next part will include the results from the characterization and validation of the ProtoDUNE-DP PDS and LCS components before their installation. The results from additional studies on the PMT response linearity and the PMT behaviour with over-pressure will be discussed as well. Besides the verification of the good performance of all the elements to be installed, results of interest for other LAr experiments were obtained from these tests. The installation and operation phases in ProtoDUNE-DP, highlighting both the achievements and the issues that were found, will be reviewed at this point.

The studies that will be presented next cover the characterization of the low-energy background detected by the PDS, the quantification of the electric field impact on the light yield, the evaluation of the Rayleigh scattering affecting the light propagation, and the analysis of the PMT detection efficiency. The VUV reflectivity of the detector materials will be also analyzed. Finally, the estimation of the cosmic muon flux crossing the TPC as well as the study of the calorimetric capacity of the PDS will be reported. All these parameters and phenomena are critical aspects in the operation of a LAr detector and the ProtoDUNE-DP light data have enabled to develop an unprecedented investigation on them.

The last part of the dissertation will summarize the simulation-based studies on the supernova burst trigger capabilities with the PDS of a 12.1-kt active mass DP LAr TPC as the one proposed for a DUNE FD module. Several configurations of WLS reflective foils installed in the TPC will be compared. The findings on the topic will enhance the important role of an efficient photon detection to accomplish the measurement of interactions of low-energy particles like SN neutrinos in a LAr TPC.

Introducción

Los descubrimientos en física de neutrinos logrados durante el último medio siglo han tenido un profundo impacto no solo en el Modelo Estándar de la física de partículas sino también en otros campos como física de astropartículas y cosmología. En concreto, hace unos veinte años, la observación del mecanismo de la oscilación de neutrinos, que implica que los neutrinos tienen masa, transformó completamente los objetivos y perspectivas de los experimentos de neutrinos. Aunque tienen el potencial de responder a varias cuestiones fundamentales relacionadas con la naturaleza de la materia y la evolución del universo, muchas de las propiedades del neutrino siguen todavía sin conocerse y, por tanto, se necesita más investigación.

DUNE (*Deep Underground Neutrino Experiment*) es un experimento de nueva generación concebido para realizar medidas de oscilaciones de neutrinos a larga distancia, astrofísica de neutrinos y búsquedas de la desintegración del protón. Tiene como objetivo abordar temas clave, como la medida de la fase de violación CP en el sector leptónico y la determinación del orden de masas de los neutrinos. El programa de física también incluye la detección del flujo de neutrinos electrónicos del estallido de una supernova. DUNE es un proyecto vanguardista basado en la colaboración internacional de más de 1300 personas. El experimento consistirá en un detector cercano multi-propósito situado justo tras el potente haz de neutrinos de Fermilab y un detector lejano de gran masa a 1.5 km bajo tierra en SURF a 1300 km. Concretamente, el detector lejano de DUNE tendrá cuatro módulos de cámara de proyección temporal de argón líquido (*liquid-argon time-projection-chamber*, LAr TPC) de 17 kt cada uno, complejos detectores de partículas nunca antes contruidos a tan gran escala.

El principio de funcionamiento básico de una LAr TPC es la detección de cargas de ionización generadas por la interacción de una partícula con los átomos de argón. Dichas cargas derivan gracias a un campo eléctrico hasta ser recogidas en el ánodo. Además, siendo el argón un excelente centelleador, también se producen señales de luz de centelleo, cuya detección proporciona información temporal fundamental para la reconstrucción de trazas y el disparo de eventos que no vienen del haz. Aunque la operación de una LAr TPC conlleva algunos retos técnicos, el aparato permite obtener imágenes en 3D, una excelente identificación de partículas y una extraordinaria resolución en energía. Las principales tecnologías de LAr TPC son la de fase única, con el detector lleno de argón líquido, y la de doble fase, en la cual se utilizan tanto argón líquido como argón gaseoso.

Para demostrar la viabilidad del detector lejano de DUNE, se está desarrollando actualmente un programa de I+D en la Plataforma de Neutrinos del CERN. Concretamente, ProtoDUNE Dual Phase (DP), una LAr TPC de doble fase con 300 t de masa activa y 6 m

de deriva vertical, tomó datos de la interacción de muones cósmicos en 2019-2020 con el objetivo de validar la tecnología de doble fase para DUNE. Se trata de la mayor LAr TPC de doble fase jamás operada. La tecnología de doble fase se basa en un volumen de argón líquido con una capa superior de argón gaseoso que permite la amplificación de las señales. A pesar de las diversas ventajas con respecto a la fase única (como la mayor resolución espacial y las distancias de deriva más largas), el enfoque de doble fase es más novedoso y presenta más retos que la madura tecnología de fase única.

Esta tesis se centra en el estudio del funcionamiento del sistema de detección de luz (*photon detection system*, PDS) de ProtoDUNE-DP, formado por 36 fotomultiplicadores (*photomultipliers*, PMTs) colocados en el suelo del criostato. Como los PMTs no son sensibles a la luz de centelleo en el rango ultravioleta, se instalaron dos desplazadores de longitud de onda para convertir la luz a 127 nm en fotones visibles: una lámina de PEN sobre 30 PMTs y un recubrimiento de TPB en 6 PMTs. El diseño de ProtoDUNE-DP cuenta con un sistema de calibración del PDS (*light calibration system*, LCS) para monitorizar la respuesta de los PMTs.

Los primeros capítulos de esta tesis extenderán esta introducción, ya que ofrecerán un resumen de la física de neutrinos, de los principios de una LAr TPC y del experimento DUNE. A continuación, se comentarán las características de los diferentes sistemas de ProtoDUNE-DP, con el foco en el PDS y el LCS. La siguiente parte incluirá los resultados de la caracterización y validación de los componentes del PDS y del LCS de ProtoDUNE-DP antes de la instalación. Así mismo, se discutirán los resultados de estudios adicionales sobre la linealidad de la respuesta del PMT a temperaturas criogénicas y del comportamiento del PMT sometido a sobrepresión. Además de servir para verificar el buen funcionamiento de todos los elementos antes de ser instalados, de estas pruebas se obtuvieron resultados de interés para otros experimentos que usan argón líquido. Se explicarán las fases de instalación y operación de ProtoDUNE-DP, señalando tanto los logros como los problemas que se encontraron.

Los estudios que se presentarán a continuación cubren la caracterización del fondo de baja energía detectado por los PMTs, la cuantificación del impacto del campo eléctrico en la producción de luz, la evaluación de la dispersión de Rayleigh que afecta a la propagación de la luz, y el análisis de la eficiencia de detección del PMT. Se analizará también el efecto de la reflectividad de los materiales del detector para luz ultravioleta. Por último, se presentarán la estimación del flujo de muones cósmicos cruzando el detector y el estudio de la capacidad calorimétrica del PDS. Todos estos parámetros y fenómenos son aspectos críticos en la operación de un detector de argón líquido, y los datos de luz de ProtoDUNE-DP han permitido desarrollar una investigación única sobre ellos.

La última parte de la tesis resumirá los estudios de simulación de las capacidades para el disparo de supernovas con el PDS de una LAr TPC de 12.1 kt de masa activa como el propuesto para un módulo de doble fase en DUNE. Se compararán varias configuraciones de paneles reflectantes con desplazador de longitud de onda instalados en la TPC. Los hallazgos en el tema realzarán el importante papel de una detección de fotones eficiente

para conseguir la medida de interacciones de partículas de baja energía, como los neutrinos de supernova, en una LAr TPC.

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Neutrino physics

“ *I have done a terrible thing,
I have postulated a particle that cannot be detected.*

— **Wolfgang Pauli**
(Statement of 1930)

1.1 Introduction

Neutrinos have demonstrated to be extremely elusive particles, forcing particle physicists to build giant detectors in underground mines, at the bottom of the sea or even among the Antarctic ice to detect them. Although huge progress has been made in the comprehension of the neutrino interactions and properties, both from the theoretical and experimental points of view, there is still a long way ahead for the complete understanding of these elementary particles.

This chapter provides a brief introduction to neutrino physics. Section 1.2 covers the main neutrino properties in the standard model (SM) framework. Some historical milestones in neutrino physics, from its discovery to the latest advances in the field, are reviewed in Section 1.3. The formalism of neutrino oscillations, a quantum phenomenon beyond the standard model (BSM), is presented in Section 1.4, giving an overview of the oscillation parameters and the long-baseline experiments designed to measure them in Section 1.5. The basic features of the neutrino burst emitted in a core-collapse supernova, which carries valuable information on the explosion mechanisms as well as the neutrino properties, are reported in Section 1.6. Finally, the topics still under investigation on neutrino physics, some of them related to fundamental questions about the universe, are summarized in Section 1.7.

1.2 Neutrino properties

The SM of particle physics is a gauge theory describing the strong, electromagnetic and weak interactions in the universe as well as the elementary particles [1]. It is based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$ (corresponding to quantum chromodynamics (QCD), weak isospin and hypercharge groups, respectively), spontaneously broken to $SU(3)_C \times U(1)_{EM}$. In the SM, neutrinos are fermions, basic constituents of matter. In particular, they are neutral massless leptons (half-integer spin) that only interact via

weak interactions with matter. However, it is known now that these elementary particles have non-zero mass because they undergo flavor oscillations as they propagate, being neutrinos an example of BSM physics. As other leptons, neutrinos and antineutrinos (the corresponding antiparticles) exist in, at least, three flavors (generations). Namely, electron, ν_e , muon, ν_μ , and tau, ν_τ , neutrinos are associated to the three charge leptons as:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad (1.1)$$

Despite having mass, neutrinos are much lighter than their corresponding charged partners. A fourth neutrino family not having SM gauge interactions, the sterile neutrino [2], has been proposed but not discovered so far. Under CPT (charge, parity and time reversal) symmetry conservation, neutrino is a left-handed particle and antineutrino is a right-handed antiparticle; a right-handed neutrino, not observed for the moment, would not interact via any of the mentioned interactions. In the SM, neutrinos only can interact via charge-current (CC) weak interaction with exchange of a $W^\pm$ boson and neutral-current (NC) weak interaction with exchange of a Z^0 boson as:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \sum_l \bar{\nu}_{Ll} \gamma^\mu l_L^- W_\mu^+ + \text{h.c.}, \quad (1.2)$$

$$-\mathcal{L}_{NC} = \frac{g}{2 \cos \theta_W} \sum_l \bar{\nu}_{Ll} \gamma^\mu \nu_{Ll} Z_\mu^0, \quad (1.3)$$

where $l = e, \mu, \tau$; g is the coupling constant associated to $SU(2)$; and θ_W is the Weinberg angle. In the CC interactions the corresponding charged leptons are involved whereas in NC they are not. Equation 1.3 determines the decay width of the Z^0 boson into light left-handed neutrinos and, thus, allows the determination of the number of light neutrinos: $N_\nu = 2.984 \pm 0.008$ [3], at present.

In the SM, the fermion masses are generated via a Yukawa coupling between the two helicity states of the particle. As right-handed neutrino states are absent in the SM, the model predicts neutrinos are precisely massless. However, in view of the discovered neutrino mixing, the neutrino mass can be included in two ways:

- Dirac neutrinos: the SM is extended by adding a set of three right-handed neutrino states that couple to matter just through neutrinos masses (proportional to Higgs field value), and lepton number conservation is imposed:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\mu \bar{\nu}_R \nu_L + \text{h.c.} \quad (1.4)$$

This scenario does not explain why neutrinos are much lighter than their charged leptonic partners since the same mechanism to acquire mass is assumed.

- Majorana neutrinos: the antiparticle of the left-handed state is identified with the right-handed state, and total lepton number is violated by two units:

$$\mathcal{L} = \mathcal{L}_S M - \frac{1}{2} M_\mu \overline{\nu_L^C} \nu_L + \text{h.c.} \quad (1.5)$$

where $\overline{\nu_L^C}$ is the charge-conjugated field and is left-handed. In this case, the *see-saw mechanism* [4] aims at explaining the relative small neutrino masses compared to other heavier fermions. This mechanism requires not only the observed light left-handed neutrino but also a very heavy right-handed neutrino, not allowed in the SM.

Whether neutrinos are Dirac or Majorana particles has not been determined yet. On the other hand, the absolute mass of the neutrinos is assessed by studying the conservation of momentum and energy in weak interactions.

It is worth remarking that, since their discovery, neutrinos are the less known leptons in the SM and, hence, intense investigation on their properties and behaviour has been carried out in the last decades. As it will be shown in the next section, both theoretical work and experimental advances have been developed in parallel up to the current picture on neutrino physics.

1.3 Milestones in neutrino physics

Nuclear beta decay ($n \rightarrow p + e^- + \bar{\nu}_e$) was discovered in 1899 by E. Rutherford. In 1930, W. Pauli hypothesized the existence of the neutrino [5] in order to explain the continuous energy spectrum of the beta rays found by J. Chadwick in 1914. The concept of neutrino, a new neutral particle that, according to Pauli, *cannot be detected*, was the solution to the apparent contradiction of the principle of energy conservation in beta decays. The name neutrino, proposed by E. Fermi who later developed a theory for beta decay, means “little neutral one” in Italian. The existence of the neutrino was experimentally confirmed in 1956 by F. Reines and C.L. Cowan in the Savanna River Nuclear Reactor [6] using a liquid scintillator to detect electron antineutrinos interacting via inverse beta decay ($p + \bar{\nu}_e \rightarrow n + e^+$). The muon neutrino, ν_μ , was discovered in 1962 by L. Lederman, M. Schwartz and J. Steinberg in the Brookhaven National Laboratory [7]. In 1987, three experiments (Kamiokande [8], IMB [9] and a detector in Baksan [10]) observed the neutrinos from the supernova SN1987A. The tau neutrino, ν_τ , was detected in 2000 by the DONUT experiment [11].

Around 1969, the experiment by R. Davis [12] measured for the first time neutrinos from the Sun (primarily electron neutrinos) and found that the neutrino flux was significantly less ($\sim 1/3$) than the prediction from the standard solar model. “The solar neutrino problem” was confirmed by other experiments, such as SAGE, GALLEX and Kamiokande. About ten years later, Kamiokande, IMB and Soudan groups reported “the atmospheric

neutrino anomaly” [13]: they expected to detect ~ 2 times more muon neutrinos than electron ones but the $\nu_\mu:\nu_e$ ratio was found to be dependent on the distance traveled by neutrinos. Finally, the neutrino flavor oscillation with propagation, a mechanism theoretically postulated in 1957 by B. Pontecorvo [14] and implying neutrinos have mass (BSM physics), was the solution to both problems. The first clear evidence of neutrino oscillations was reported in 1998 by Super-Kamiokande for atmospheric neutrinos [15]. In 2002, SNO measured NC interactions of solar neutrinos that confirmed the oscillation of electron neutrinos to other flavors [16].

Other important achievements on neutrino physics have been completed apart from the commented above. Examples of later events are the first evidence for geoneutrinos by KamLAND in 2005 [17]; the first indications of a non-vanishing value of the 3rd mixing angle (see next section) by T2K [18] and Double Chooz [19] in 2011, and by Daya Bay [20] and RENO [21] in 2012; the first measurement of high-energy astrophysical neutrinos by IceCube in 2013 [22]; the first observation of coherent elastic neutrino-nucleus scattering by the COHERENT Collaboration in 2017 [23]; multimessenger observations of a flaring blazar coincident with high energy neutrino in 2018 [24]; and the measurement of neutrinos from the CNO cycle by Borexino in 2020 [25].

1.4 Neutrino oscillation formalism

The quantum phenomenon of neutrino oscillations implies that the neutrino CC interaction eigenstates or flavor eigenstates, α , can be expressed as linear combinations of the neutrino mass eigenstates, k , as:

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle \quad (1.6)$$

As a consequence, a neutrino created with a specific flavor can be measured with a different one after traveling some distance. Assuming three flavor eigenstates ($\alpha = e, \mu, \tau$) and three mass eigenstates ($k = 1, 2, 3$), the 3×3 unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [26] that describes the rotation is:

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = (A) \times (B) \times (C) \times (D) = \quad (1.7)$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. Thus, this neutrino mixing matrix parametrization includes three mixing angles (θ_{12} , θ_{13} and θ_{23}), the Dirac complex phase (δ) related to the CP (charge and parity) violation, and two Majorana phases (α_1 and α_2) that are not

accessible by oscillation experiments. See the best values up to date for the parameters that govern the neutrino oscillations in the next section.

Although further information on the neutrino sources and experiments involved in the oscillation measurements will be given in the next section, it is worth mentioning at this point that, in Equation 1.7, the sub-matrix (A) is called “atmospheric term” and is determined by atmospheric and long-baseline accelerator experiments; the sub-matrix (C) is the “solar term” and is determined by solar and long-baseline reactor experiments; the sub-matrix (B) is a “mixed term” determined by long-baseline and short-baseline reactor experiments; finally, (D) is the “Majorana term”, partially investigated in experiments that search for neutrinoless double beta decay.

When a neutrino created with flavor α propagates in the vacuum, its evolution with time follows:

$$|\nu_\alpha(t)\rangle = \sum_k e^{-iE_k t} U_{\alpha k}^* |\nu_k\rangle \quad (1.8)$$

being E_k the neutrino energy of the k -th mass eigenstate. The probability of flavor change from α to β is given by:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{i,k} U_{\alpha k}^* U_{\beta i} \langle \nu_i | \nu_j(t) \rangle \right|^2 = \sum_{i,k} U_{\alpha k}^* U_{\beta k} U_{\alpha i} U_{\beta i}^* e^{-i(E_k - E_i)t} \quad (1.9)$$

Then, assuming neutrinos are relativistic with energy:

$$E_k = \sqrt{p_k^2 + m_k^2} \approx p + \frac{m_k^2}{2E}, \quad (1.10)$$

the transition probability can be expressed as:

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \sum_{i,k} U_{\alpha k}^* U_{\beta k} U_{\alpha i} U_{\beta i}^* \exp\left(-i \frac{\Delta m_{ki}^2 L}{2E}\right) \quad (1.11)$$

with $\Delta m_{ki}^2 \equiv m_i^2 - m_k^2$ and L the distance between the source and the detector. The oscillation probabilities for neutrinos and antineutrinos differ ($P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$) if CP-invariance is violated in the leptonic sector.

Regarding the difference in the squares of the neutrino masses in the Equation 1.11, Δm_{21}^2 is the “solar mass splitting” whereas Δm_{31}^2 is called the “atmospheric mass splitting”, being $\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$. By convention, the choice of labels of the neutrino mass states gives a positive solar mass splitting. Two possible mass orderings or hierarchies are possible: *normal ordering* (NO) with $m_1 < m_2 < m_3$, matching the mass ordering of the charged leptons in the SM, and *inverted ordering* (IO) implying $m_3 < m_1 < m_2$ instead. The two mass scenarios are illustrated in Figure 1.1.

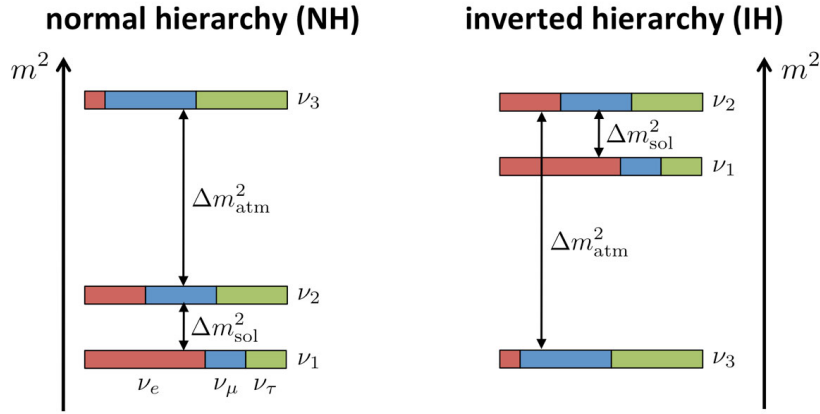


FIGURE 1.1: Two ordering or hierarchy scenarios of neutrinos masses: normal (left) and inverted (right). Figure credit: JUNO Collaboration / JGU-Mainz.

In most cases, the problem can be reduced to a simplified scenario of only two flavors due to the small value of θ_{13} . In this approach, the oscillation probability becomes:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 (\text{eV}^2) \frac{L(\text{km})}{E_\nu (\text{GeV})} \right), \quad \alpha \neq \beta \quad (1.12)$$

The oscillatory behaviour of the transition probability above motivates the name of *neutrino oscillations* for the phenomenon. The probability $P(\nu_\alpha \rightarrow \nu_\beta)$ in Equation 1.12 is called α -neutrino *disappearance* or β -neutrino *appearance*, whereas $P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - P(\nu_\alpha \rightarrow \nu_\beta)$ is called *survival probability*. Note that the oscillation phase depends on the ratio L/E in km/GeV, being the experiment baseline (length of propagation) and the neutrino energy the main parameters to take into account in the design of an oscillation experiment.

The equations discussed above correspond to oscillations in vacuum. When neutrinos travel through matter, new effects appear. For example, for electron neutrinos, non-negligible matter effects play a role in CC interactions leading to the following potential:

$$V_{CC} = \pm \sqrt{2} G_F N_e \quad (1.13)$$

where the sign $+$ ($-$) corresponds to neutrinos (antineutrinos), G_F is the Fermi constant and N_e is the electron number density. As there are neither muons nor taus in the medium, muon and tau neutrinos only interact via NC reactions during propagation. In the case of NC interactions in a neutral medium:

$$V_{NC} = \mp \frac{\sqrt{2}}{2} G_F N_n \quad (1.14)$$

where the sign $-$ ($+$) corresponds to neutrinos (antineutrinos) and N_n is the neutron number density.

Then, neutrino oscillations in a medium can be described as in vacuum but with an effective mass matrix, $\tilde{M}_\nu^2$, given by:

$$\tilde{M}_\nu^2 = M_\nu^2 \pm 4E_\nu V_m \quad (1.15)$$

with

$$V_m = \begin{pmatrix} V_e = V_{CC} + V_{NC} & 0 & 0 \\ 0 & V_\mu = V_{NC} & 0 \\ 0 & 0 & V_\tau = V_{NC} \end{pmatrix} \quad (1.16)$$

The flavor oscillation depends on the matter density, which varies along the neutrino path in the medium. If the variation is slow, the adiabatic transition approximation allows a simpler solution of the propagation equations, including a resonance condition in the oscillation amplitude. The adiabatic conversion of one type of neutrinos to another is known as the Mikheev-Smirnow-Wolfenstein (MSW) effect [27].

1.5 Oscillation parameters and long-baseline experiments

As neutrino oscillations are BSM physics, their discovery had a deep impact not only on particle physics, but also on astroparticle physics and cosmology. At present, precision measurements of the neutrino oscillation parameters lead the physics program of many modern neutrino experiments. Each experiment has a particular sensitivity to some oscillation parameters and, hence, the combination of the different experiment outputs is essential to perform a global fit and, hence, to obtain the best estimation of all parameters.

The neutrino sources cover a wide range of energies (10^3 - 10^{15} eV) and can be divided into two types: 1) natural sources: relics of the Big Bang, the Sun and other burning stars, supernovas, interaction of cosmic rays in the atmosphere and radioactive decays; and (2) artificial sources: particle accelerators and nuclear reactors. In the case of neutrinos that are artificially produced, the experiments detecting them can be long-baseline (LBL) or short-baseline (SBL), depending on the neutrino propagation distance from the source (accelerator or reactor) to the detector (LBL if $L/E > 100$ km/GeV). Since neutrinos are extremely weakly interacting particles, their detection in experiments is challenging. In addition, the neutrino interaction cross-section is poorly known in the energy range of interest in atmospheric and accelerator experiments (about 1 GeV), whereas it is well known at lower (< 100 MeV) and higher (10^2 - 10^7 GeV) energies where less complex processes are involved.

The best fit magnitudes and confidence intervals from using all neutrino oscillation data available up to July 2020 are listed in Table 1.1. The values of Δm_{ij}^2 are known at better than 3% while $\sin^2 \theta_{ij}$ are known at better than the 5% level. Figure 1.2 presents

	Normal ordering (best fit)		Inverted ordering ($\Delta\chi^2=7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \rightarrow 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \rightarrow 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \rightarrow 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \rightarrow 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \rightarrow 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \rightarrow 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02050 \rightarrow 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \rightarrow 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \rightarrow 369$	282^{+26}_{-30}	$193 \rightarrow 352$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
$\frac{\Delta m_{3l}^2}{10^{-3} \text{ eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \rightarrow +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \rightarrow -2.414$

TABLE 1.1: Oscillation parameters: best values and confidence intervals from the global fit for the two possible mass orderings. Values from [28].

Experiment	Run	Beam	E_ν (GeV)	L (km)	FD technology	FD mass (kt)
K2K [29]	1999-2004	KEK	1.0	250	Water Cherenkov	50
MINOS [30]	2005-2016	NuMI	3.3	735	Steel-scintillator	5.4
OPERA [31]	2008-2012	CNGS	17	732	Nuclear emulsion	1.25
T2K [32]	2010-2026	J-PARC	0.6	295	Water Cherenkov	50
NOvA [33]	2013-2021	NuMI	2.0	810	Liquid scintillator	14
DUNE [34]	2026-	NuMI	2.1	1300	LAr TPC	40
T2HK [35]	2026-	J-PARC	0.6	295	Water Cherenkov	188

TABLE 1.2: Features of some past, current and future long-baseline neutrino experiments. Tentative dates are indicated in italics.

graphically the global fit results. These values are the result of more than twenty years of intense research carried out in diverse neutrino experiments with different neutrino sources. Solar, atmospheric, reactor and accelerator experiments have been combined to obtain the best fit results [28].

Focusing on the LBL accelerator experiments (see examples listed in Table 1.2), they usually employ a $\mathcal{O}(\text{GeV})$ muon-neutrino beam, a near detector (ND) $\mathcal{O}(100\text{-}1000 \text{ m})$ downstream the neutrino source and a far detector (FD) located at $\mathcal{O}(100\text{-}1000 \text{ km})$ away. As commented before, the setup of LBL experiments corresponds to a ratio of $L/E > 100 \text{ km/GeV}$. The goal of the ND is to measure the unoscillated neutrino flux and

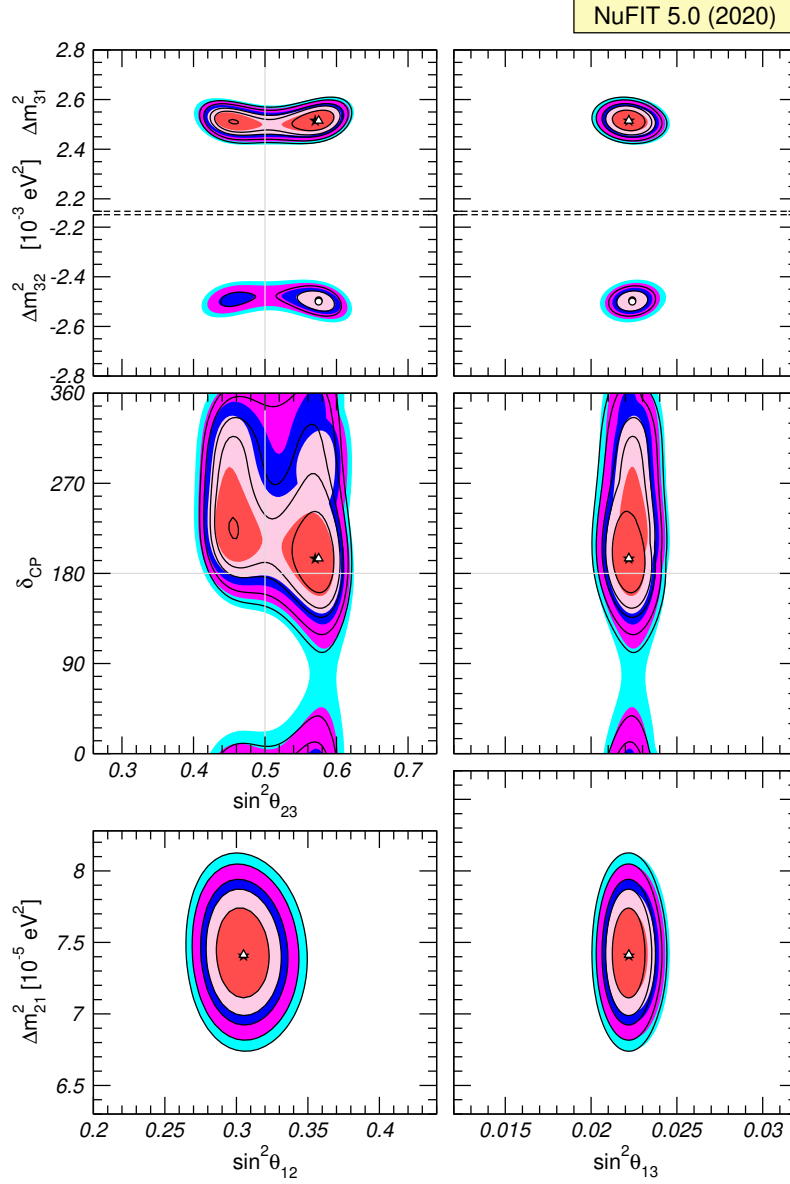


FIGURE 1.2: Global oscillation analysis for three neutrinos: two-dimensional projections of the allowed six-dimensional region after minimization with respect to the undisplayed parameters. The different contours correspond to 1σ , 90%, 2σ , 99% and 3σ CL. Figure from [28].

the purpose of the FD is to detect the neutrinos after propagating hundreds of kilometers through Earth. In this way, matter effects can be well studied. Either the ν_μ disappearance or the ν_e and ν_τ appearance are measured. The option to convert the neutrino beam into an antineutrino source enhances the capabilities of these experiments.

The current LBL accelerator experiments are NOvA [33] and T2K [32] (see features in Table 1.2). These experiments fit both disappearance and appearance data to improve their sensitivity. While NOvA does not observe strong neutrino-antineutrino asymmetry in ν_e appearance, T2K finds more appearance of ν_e than of $\bar{\nu}_e$. Figure 1.3 shows a comparison between their results for the two mass ordering scenarios. Although NO is mildly preferred by both of them, in view of these results, a joint fit might converge on an IO solution.

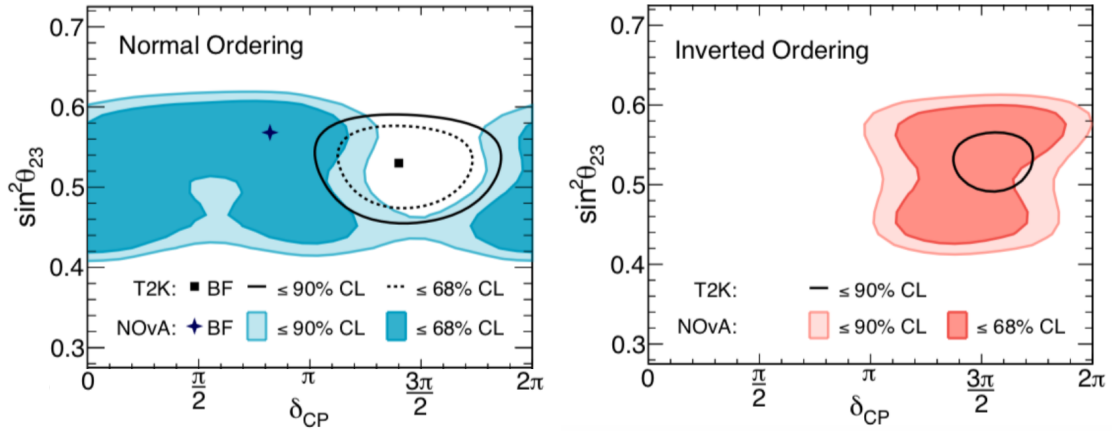


FIGURE 1.3: Confidence level contours in $\sin^2 \theta_{23}$ versus δ_{CP} for NO (left) and IO (right), including results from NOvA [33] and regions reported by T2K in [36]. Figure taken from [33].

Thus, the two collaborations are working on a full joint neutrino oscillation analysis (to be released soon) by combining the LBL data from phase I of each experiment.

DUNE [37] and T2HK [35] (Hyper-Kamiokande or Hyper-K detector) are the forthcoming generation of accelerator experiments with LBL. The first results from them are expected by the late 20s. Their main target is the precise determination of the neutrino oscillation parameters but also they have an unprecedented potential to address other related questions such as the neutrino mass ordering (relying on matter effects and/or atmospheric neutrinos), the value of δ_{CP} (based on the observation of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and the octant of θ_{23} (also thanks to $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ measurements). In particular, DUNE design counts on the most-intense neutrino source in the world, a leading-edge FD and the longest baseline ever. Thanks to these features, it will bring exceptional insight into the neutrino picture in the next decades. Being DUNE the motivation behind this thesis, its particular sensitivities to answer questions on neutrino physics will be further discussed in Section 3.4.

The problem of the neutrino mass ordering is expected to be resolved to a precision of 5σ by DUNE after two years of running thanks to enhanced matter effects and by Hyper-K after ten years through atmospheric neutrino measurements. In the latter case in which atmospheric neutrinos are studied, the reached sensitivity strongly depends on the θ_{23} octant, still to be established. While the absolute squared mass differences $|\Delta m_{ij}^2|$ and the order of m_1 and m_2 have been already measured, the sign of Δm_{13}^2 (> 0 for NO and < 0 for IO) is still unknown. Recent experiments have investigated the topic, but their conclusions are in tension [38] and only next-generation experiments (with larger target volume and baseline) will be able to determine the mass ordering at a high confidence level. The enhancement and suppression of the oscillation probability for neutrinos and antineutrinos, respectively, in the NO scenario (opposite effect in the IO case) will lead to the solution.

DUNE and Hyper-K will also determine at 5σ of significance the value of the CP-violation phase in the leptonic sector. Although CP violation in the neutrino sector is favored by the best fit to available data [28], the CP-phase value is poorly constrained so far. LBL accelerator experiments explore the δ_{CP} value by comparing the neutrino and antineutrino oscillation probabilities. The observation of $\delta_{CP} \neq 0$ or $\delta_{CP} \neq \pi$ would imply CP violation and, thus, that neutrinos and antineutrinos interact differently. Thus, it would help to better understand the origin of the baryon asymmetry that led to the current matter-antimatter asymmetry in the universe.

It is worth pointing out that the current LBL neutrino oscillation experiments are optimized to study the physics around the first oscillation maximum (first peak of $P(\nu_\mu \rightarrow \nu_e)$ vs. L/E), in which the CP violation in the oscillation probabilities is smaller than the matter asymmetry. As a consequence, additional information is required to determine the origin of the asymmetry. In the case of the future DUNE, its long baseline and wide-band neutrino beam will enable to explore part of the second oscillation maximum (second peak) and, thus, to achieve a good sensitivity to CP violation independently of the mass ordering [39, 40]. Hyper-K, on the contrary, can only access to the first oscillation maximum for T2HK baseline. In this regard, Hyper-K collaboration envisions a second detector in Korea at a baseline of ~ 1100 km (T2HKK) for a qualitative and quantitative improvement in sensitivity [35]. The two different baseline oscillation measurements (at 295 km and 1100 km) will allow breaking the parameter degeneracies.

Finally, the octant in which θ_{23} lies is also investigated in LBL experiments. Whether $\theta_{23} < \pi/4$ (first octant) or $\theta_{23} > \pi/4$ (second octant) remains unknown, but a mild preference for the second octant is obtained from the global fit of the available data [28]. The octant degeneracy is a problem affecting the sensitivity to measure other oscillation parameters and, thus, the octant discrimination will improve the overall knowledge of neutrino oscillations.

Other neutrino experiments (non-accelerator) that will contribute in the next decade (results expected in 2022-2026) with neutrino oscillation and mass hierarchy measurements are KM3NeT-ORCA [41], PINGU [42] and JUNO [43]. The first two experiments will detect atmospheric neutrinos while the last one is a medium baseline ($L = 50$ km) reactor neutrino experiment.

1.6 Supernova neutrinos

A type II supernova occurs when a massive star ($> 8 M_\odot$) reaches the end of its life [44]. The star develops a layered structure with an iron core and the heavier elements in the deeper shells. Then, some of the mass of the star begins to flow into its core, which is eventually so heavy that, when the critical mass of $\sim 1.4 M_\odot$ is reached, it cannot resist its own gravitational force and collapses, leading to a giant explosion where $\sim 3 \cdot 10^{53}$ erg of

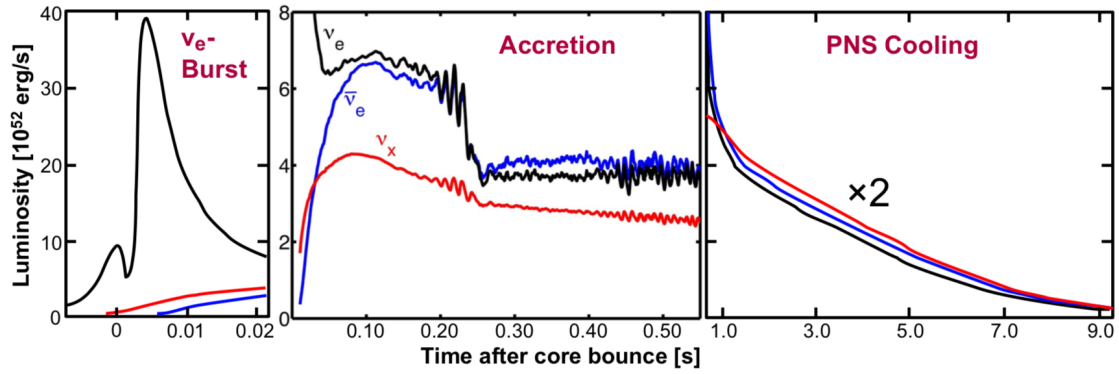


FIGURE 1.4: Neutrino luminosities (ν_e in black; $\bar{\nu}_e$ in blue, and ν_x in red as one species of ν_μ , $\bar{\nu}_\mu$, ν_τ , $\bar{\nu}_\tau$) during the main supernova neutrino-emission phases. The left panel presents the prompt burst of electron neutrinos from the shock breakout; the middle panel is the accretion phase; and the right panel shows the decay of the neutrino luminosities in the neutrino-cooling phase (scaled up by a factor of 2). Figure taken from [48].

binding energy is released. The expected frequency of such an energetic phenomenon in our Galaxy is about one every thirty years [45].

Neutrinos and antineutrinos of all flavors are emitted in a supernova explosion [46]. The high density of the core (10^{12} - 10^{14} g/cm³) prevents the photon emission and, hence, over 99% of the gravitational binding energy is released in form of neutrinos: about 10^{58} neutrinos with energies ~ 10 MeV. As the supernova neutrino burst precedes the electromagnetic signal, its detection can issue a prompt alert to the astronomical community. In the current era of multi-messenger astrophysics, the organization created around this idea is the SuperNova Early Warning System (SNEWS) collaboration [47], which counts on several supernova neutrino-sensitive experiments.

The underlying mechanisms of a core collapse are still not well understood, but significant progress on the topic has been made in the past decades. In particular, the observation of neutrinos from the supernova SN1987A in the Large Magellanic Cloud (about 50 kpc from Earth) was a crucial milestone. Despite only about 20 neutrino events were detected by Kamiokande [8], IMB [9] and Baksan [10] detectors, these measurements confirmed the existing physical picture of the core-collapse process. Since then, there have been both theoretical and experimental advances towards a much deeper understanding from the next supernova neutrino detection.

From the point of view of the neutrino emission, the core-collapse event can be divided into three phases (see Figure 1.4):

- **Infall stage (up to 20 ms) and neutronization burst (from core bounce to 50 ms):** a first burst of electron neutrinos is emitted while the core collapses. Then, neutrinos are trapped and an elastic core bounce occurs, resulting in a shock wave. The supernova neutrino signal continues with a short and intense flux (neutronization or *break-out* burst), primarily composed of electron neutrinos. An energy of about $\sim 3 \cdot 10^{51}$ erg is radiated. This signal indicates that the shock has crossed the neutrinosphere (surface of neutrino trapping).

- **Accretion phase (from 50 ms to 200 ms):** during the accretion of matter (falling onto the collapsed core), the electron-neutrino luminosity rapidly decreases, and significant flavor differences of fluxes arise.
- **Cooling period (from 0.2 s to 9 s):** it represents the main part of the signal (about 10 s). The star releases its trapped energy ($2\text{--}4\cdot 10^{53}$ erg) until a neutron star or a black hole is formed.

The variation of the flavor content and spectra of the neutrino signal along the 10 s of the stages listed above provides valuable insight into the supernova evolution. Examples of astrophysical observables are the sharp signal cutoff if a black hole is formed, and the time-dependent change in flavor and spectrum as a shock wave propagates. SASI (standing accretion shock instability) effects [49] could be observed as an oscillatory and flavor-dependent modulation of the flux. The neutronization burst, strongly or partially suppressed depending on the mass ordering, is another interesting signature of the neutrino flux.

The complementarity of the informations from different supernova neutrino experiments is key. While Super-Kamiokande is the principal supernova neutrino experiment at the time of this writing, Hyper-Kamiokande, JUNO and DUNE will be the leading supernova neutrino detectors in the new generation. Hyper-K (water Cherenkov detector) and JUNO (liquid scintillator detector) will be sensitive primarily to $\bar{\nu}_e$ whereas DUNE (LAr TPC) will be to ν_e . Potentially, Hyper-K will have enormous statistics (over $5\cdot 10^4$ events for a supernova at 10 kpc) and will be able to distinguish with high accuracy between different supernova models for a supernova at a distance of up to 100 kpc [50]. JUNO may have the capability to measure the initial supernova neutrino fluxes, to constrain the neutrino mass scale and ordering, and to investigate the collective neutrino oscillations [51]. It is expected that a supernova at 10 kpc will yield about $5\cdot 10^3$ events in JUNO. Finally, the ν_e detection in DUNE will enable to explore the initial phase of the burst in a unique way. For details about the prospects on the supernova neutrino detection in DUNE, see Section 3.4.2.

1.7 Other open questions

Despite the remarkable advances in neutrino physics during the last decades, some questions are still unanswered and exciting discoveries are expected in the near future. The determination of the neutrino mass ordering, the measurement of the δ_{CP} value and the discrimination of the θ_{23} octant were already described in Section 1.5, explaining the approach followed in the LBL accelerator neutrino experiments to address these aspects. Three additional open questions on neutrino physics are briefly discussed below.

The existence of sterile neutrinos [2], proposed as a fourth neutrino family that would not interact via SM interactions, has not been confirmed yet experimentally. GALLEX and SAGE measured a Gallium neutrino anomaly [52], and LSND and MiniBooNE found

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam [53]. MiniBooNE observed an excess of ν_e events as well. These results do not agree with the three-neutrino paradigm and suggest that there may be one or more additional neutrinos with $\mathcal{O}(\text{eV})$ mass. Nevertheless, other neutrino and cosmological experiments agree with the picture of only three neutrinos. For instance, Planck excludes a fully-thermalized fourth neutrino state ($N_{eff} = 4$) at 2.7σ - 5.3σ , depending on the dataset [54].

Another question introduced along this chapter is whether neutrinos are either Dirac or Majorana particles. Experimentally, the hypothetical neutrinoless double beta decay [55] is a process of BSM physics in which matter is created without the balancing emission of antimatter (the total lepton number is violated). Such a process is investigated in different experiments (like MAJORANA [56], GERDA [57] or CUORE [58]) and its observation would demonstrate the neutrino to be a Majorana fermion and, thus, its own antiparticle. If discovered, neutrinoless double beta decay would be the slowest process ever observed (half-life $\geq 10^{26}$ years). As a consequence, the main challenge in these experiments is the control of the backgrounds to the levels required for sensitivity of such an extremely slow process.

Lastly, the measurement of the tiny absolute neutrino mass (about few tens of meV) is still a significant challenge [59] more than twenty years after the discovery of the non-zero neutrino mass. Unfortunately, neutrino oscillation experiments are only sensitive to the squared mass difference (they can only set a lower limit for neutrino masses) and, thus, a different approach is required. The absolute neutrino-mass scale is the target of beta-decay experiments like KATRIN that, for the moment, has provided an upper limit on the absolute mass scale of neutrinos of 1.1 eV (90% confidence level) [60]. Likewise, experiments searching for the very rare neutrinoless double beta decay may be able to determine the absolute neutrino-mass scale. Finally, neutrino masses can be also assessed through cosmological observations, such as the ones from Planck, indicating $\sum m_\nu < 0.12$ eV (95% confidence level) [61].

LAr TPC principles

“If you can’t explain it simply,
you don’t understand it well enough.

— Albert Einstein

2.1 Introduction

This chapter presents an overview of the operation principles of a liquid-argon time-projection chamber (LAr TPC), a particle detector broadly used in neutrino experiments (like DUNE, the one motivating this thesis) and direct dark matter searches. The track reconstruction performed in a LAr TPC is based on the detection of the ionization charge produced by interacting particles in a LAr volume. The electrons are drifted by an uniform electric field towards a readout plane. Besides, complementary information can be derived from the detection of the scintillation light that is also produced when charged particles cross the LAr medium.

First of all, Section 2.2 summarizes the basics of a TPC detector, briefly explaining the design as well as the recombination, electron attachment and space-charge effects that impact on the track reconstruction. The properties of argon and its advantages to be used as target medium in a TPC are reviewed in Section 2.3. Then, Section 2.4 describes the single-phase and dual-phase LAr TPC technologies. The scintillation light mechanisms, including production, propagation and detection in LAr, are discussed in Section 2.5. To conclude, the interest of the light in a LAr TPC is commented in Section 2.6.

2.2 TPC basics

A TPC is a detector providing direct 3D track information. It was proposed in 1974 by D. Nygren [62] as a drift chamber proving the identification of the passing particle from its energy loss per crossed distance (dE/dx). The first TPC was operated in 1983 in the PEP4 experiment at SLAC. After that, many other TPCs were constructed and operated in both collider and fixed-target experiments, increasing the dimension and the number of readout channels. Although the complex operation of a TPC involves some technical challenges, it provides a fine imaging, excellent particle identification and extraordinary energy resolution. Thus, it is the detection technology chosen by many particle experiments with different purposes.

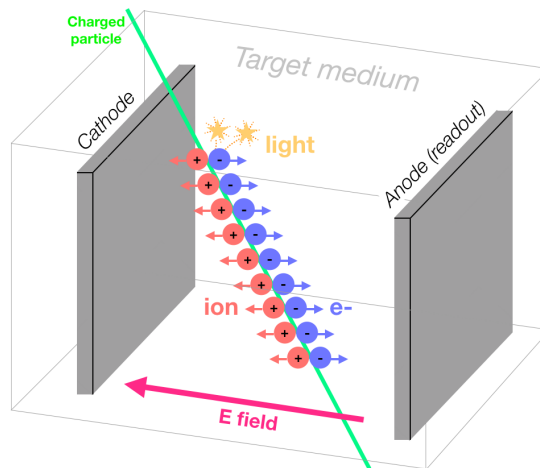


FIGURE 2.1: Diagram of the basic TPC operation, where signals from ionization charge and scintillation light are produced and detected (note that photon sensors are not displayed) for the 3D track reconstruction.

The main TPC components are indicated in Figure 2.1. When a charged particle passes through the TPC sensitive volume, which is filled with gas or liquid (target medium), it produces ionization charge (ion-electron pairs) along its path. Moreover, if the target medium is a scintillator, the crossing particle also generates scintillation photons. For a minimum ionizing particle (MIP), the number of ionization electrons is expected to be proportional to the transferred energy (linear energy transfer or LET regime). Therefore, a TPC can also work as an hadronic and electromagnetic calorimeter with fine granularity. A high electric field is responsible for the drift of the ionization electrons towards a charge collection anode, where a 2D projection of the particle track can be reconstructed with a resolution set by the anode segmentation. The electric field also suppresses the immediate recombination of the pairs by moving the electrons apart. For an accurate track reconstruction, the electric field is kept very homogeneous within the active volume using a field cage which consists of conducting rings to divide the potential from the cathode down to the anode. Additionally, a high magnetic field parallel to the electric field can be applied to determine the momentum of the ionizing particle from the curvature of its trajectory.

The collection anode usually consists of two induction wire planes (bipolar signals) and one collection wire plane (unipolar signal). The angles between wires of different layers are chosen to reduce ambiguities in event reconstruction. The readout system must be non-destructive as at least two planes with different wire orientations are required to obtain the two coordinates perpendicular to the drift direction. In order to achieve an absolute 3D reconstruction of the particle track, the drift time of the electrons (difference between the time of arrival to the anode and the initial time of the interaction or t_0) is needed. Such a timing information is easily retrieved in the case of beam events but it can be more challenging to obtain in the case of non-beam events. In the latter scenario,

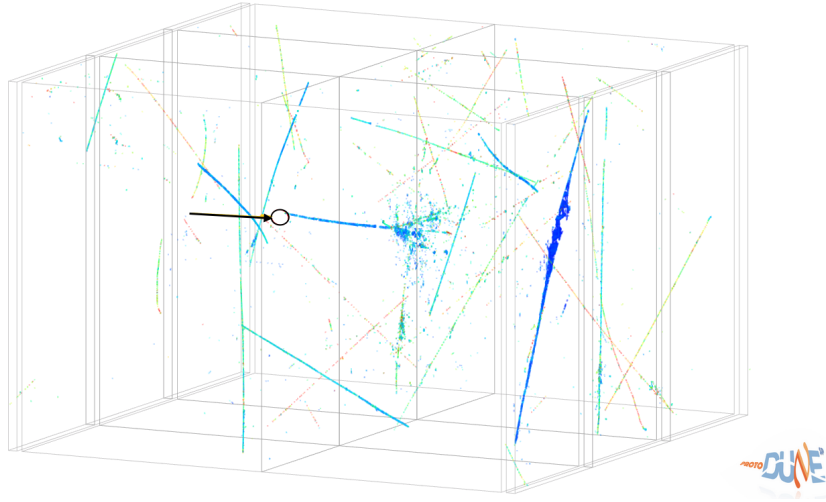


FIGURE 2.2: Test-beam event recorded by ProtoDUNE-SP (LAr TPC): a pion (π^+) enters the TPC (black arrow and circle) and interacts. The other tracks correspond to cosmic muons that cross the detector at the same time.

the scintillation light detection in the TPC (see Section 2.5) allows the t_0 determination. Figure 2.2 shows as an example of a beam event reconstructed in a TPC.

Concerning the target medium of the TPC, the first detectors employed noble gases or mixtures but, in a few years, liquified noble gases (like helium, neon, argon, krypton or xenon) started to be used as well. The advantages are that liquids present higher density and lower electron diffusion (spread over drift) compared to gases. The higher density is critical for the study of processes with very low cross-section such as neutrino or direct dark matter interactions, while the lower electron diffusion improves the spatial resolution over long drift distances. Regarding the electron diffusion, when the electric field is not null, the diffusion is no longer isotropic and takes place predominantly in the plane perpendicular to the field. In this way, two diffusion coefficients are needed to characterize the medium, as presented later in Table 2.1 for LAr.

When an incident particle loses its energy (E_0) in a TPC [63], the atoms in the active medium are either ionized or excited according to¹:

$$E_0 = N_{ion} \cdot E_{ion} + N_{exc} \cdot E_{exc} + N_{ion} \cdot \epsilon \quad (2.1)$$

where N_{ion} and N_{exc} are the number of electron-ion pairs and excitons (bound-state of electron and electron-hole), respectively; E_{ion} and E_{exc} are the energy required to ionize and excite the medium, respectively; and ϵ is the average kinetic energy of sub-excitation

¹The transferred energy can also generate heat albeit this contribution can not be determined in a TPC.

electrons. Dividing Equation 2.1 by N_{ion} , the average energy to create an electron-ion pair, the so-called W-value ($W \equiv E_0/N_{ion}$), is:

$$W = E_{ion} + \frac{N_{exc}}{N_{ion}} \cdot E_{exc} + \epsilon \quad (2.2)$$

In the case of a target medium as LAr (excellent scintillator), both de-excitation and electron-ion recombination processes lead to scintillation photons ($N_{ph} = N_{exc} + N_{ion}$). Then, assuming null light quenching, the average energy for the production of a single photon, $W_{ph}(\text{max})$, can be written as:

$$W_{ph}(\text{max}) = \frac{W}{1 + \frac{N_{exc}}{N_{ion}}} \quad (2.3)$$

See values of N_{exc}/N_{ion} ratio, energies, W and W_{ph} for argon later in Table 2.1. In principle, $N_{exc}/N_{ion} \approx 0.2$ independently of the ionizing particle energy and type [93].

2.2.1 Recombination and electron attachment

Effects such as the recombination of electron-ion pairs [64] and the attenuation of the ionization charge due to the electron attachment to electronegative impurities present in the sensitive medium [65, 66] (primarily oxygen, water, nitrogen and carbon dioxide) must be taken into account. The electron-ion recombination, which also varies with the ionization density, takes place right after the ionization and generates excited atomic states that eventually release energy. On the other hand, the charge quenching caused by impurities in the medium can occur along all the drift electron path towards the anode and is determined by the concentration of contaminants. As a consequence, the TPC-based calorimetric studies must unfold these effects that degrade the detected ionization charge. The two phenomena depend on the electric field. In the case of a scintillator medium, both the recombination and the electronegative impurities also impact on the scintillation light, see Section 2.5.

2.2.2 Space-charge effects

TPCs located on the surface are crossed by a large cosmic-ray flux, mainly composed of muons. As a result, an important ionization density appears in the sensitive medium. Both ionization electrons and positive argon ions are produced, being the drift velocity at an electric field of 0.5 kV/cm of $\mathcal{O}(\text{mm}/\mu\text{s})$ for electrons and of $\mathcal{O}(\text{mm}/\text{s})$ for positive ions. Due to the significant difference between the mobilities, a large amount of positive space charge is accumulated in the detector for a longer time, leading to significant distortions of the electric field in the TPC. The pattern of the space charge depends on the convective flow of the medium, which is not symmetric.

A correction must be applied off-line to compensate the space-charge effects in the data analysis. Namely, the distortions of the electric field lead to an incorrect reconstruction of the ionization charge at the anode readout and cause changes in the electron-ion recombination with respect to the expected effect, which is usually corrected independently of the space charge. Trying to find a robust correction for space-charge effects, a recent study in [67] provides a description named *Ion Transport Model* for the electric field distortions in a TPC due to the slowly moving ions. This model has been found to agree with experimental data from the ProtoDUNE-SP experiment at surface [68]. It is worth noticing that no significant space-charge effects are expected in deep underground detectors like DUNE.

2.3 Liquid argon as target medium

In 1977, C. Rubbia proposed the use of pure LAr as the TPC sensitive medium [70]. Relevant argon properties are listed in Table 2.1. Namely, LAr TPCs like DUNE (see next chapter) allow the investigation of the neutrino (antineutrino) charged-current (CC) interaction with argon nuclei or nucleons, with a cross-section decomposed as [69]:

$$\sigma_{total} = \sigma_{QE} \oplus \sigma_{RES} \oplus \sigma_{DIS} \quad (2.4)$$

where each term corresponds to a different neutrino (antineutrino) process:

- Quasi-elastic scattering (QE): $\nu_l + n \rightarrow p + l^-$ ($\bar{\nu}_l + p \rightarrow n + l^+$).
- Resonance excitation channel (RES): $\nu_l + N \rightarrow l^- + \Delta$ ($\bar{\nu}_l + N \rightarrow l^+ + \Delta$), being N either a proton or a neutron, and $\Delta \rightarrow \pi + N'$.
- Deep inelastic interaction (DIS): $\nu_l + N \rightarrow l^- + X$ ($\bar{\nu}_l + N \rightarrow l^+ + X$).

It has to be noted that LAr is the ideal medium to detect the signatures of charged leptons involved in the neutrino reactions above because the charge deposition per unit length (dE/dx) and the event topology (decay products) enable the identification of the particle. This is essential to tag the flavor of the incoming neutrino. Besides, a key feature of LAr is that the low-energy tracks and the hadronic showers can be well distinguished. Thus, LAr detectors allow an excellent neutrino energy reconstruction and the separation of photons and electrons as well as of the separation of protons and kaons. Regarding the rejection of backgrounds, specially challenging for detectors positioned on the Earth's surface, the electromagnetic backgrounds can be effectively suppressed in LAr using pulse-shape discrimination, among other techniques. Therefore, both a good background suppression and a good signal efficiency can be achieved in a LAr TPC.

Apart from the aforementioned advantages, other qualities of LAr for TPCs are: 1) it is an efficient target thanks to the high density, 2) it is abundant in Earth's atmosphere, easy to be extracted and, hence, cheap, 3) it can be easily purified, 4) it has a large dielectric rigidity allowing operation at high voltage, and 5) It has excellent charge transport and

	Property	Value	Units
Basic	Atomic number (Z)	18	–
	Atomic weight (A)	39.948	g/mole
	LAr density	1.396	g/ml
	Gas Ar density	1.662	g/l
	Normal boiling point	87.30	K
	Temperature at triple point	83.80	K
	Dielectric constant	1.51	–
Q transport	Electron mobility	320.23	cm ² /(V·s)
	Electron drift velocity	0.160	cm/ μ s
	Ion drift velocity	8	mm/s
	Longitudinal diffusion coeff.	6.627	cm ² /cm
	Transverse diffusion coeff.	13.233	cm ² /cm
Particle passage	Molière radius	10.0	cm
	Radiation length	14.0	cm
	Nuclear interaction length	85.7	cm
	dE/dx for a MIP	2.12	MeV/cm
	Mean excitation energy	188.0	eV
	Ionization energy	15.75	eV
	N_{exc}/N_{ion}	0.21 [72], 0.19[73] 0.29[74]	–
	W-value for ionization	23.6	eV/pair
Scintillation	W_{ph} (for scintillation)	19.5 [75]	eV/ph
	W_{ph} (for Cherenkov)	2700	eV/ph
	Scintillation emission peak	127(10) [76]	nm
	Rayleigh scattering length	99.9 [77]	cm
	Absorption length	>200	cm

TABLE 2.1: Relevant physical and chemical properties of LAr [71]. All the values at 0.5 kV/cm electric field and scintillation properties for 127 nm light.

optical properties. The first point makes LAr the best option to detect neutrino interactions; the second aspect becomes a decisive factor in the case of detectors on the kt-scale; the third and fourth features simplify the TPC operation.

From the point of view of the density, LAr is more favorable than water as sensitive medium. In water Cherenkov detectors, a very large target mass of ultrapure water can be instrumented at a relative modest cost and they also allow the efficient separation of muon and electron signals. The major disadvantage of the technique is the higher energy threshold (~ 4 MeV) compared to LAr TPCs. Nevertheless, water Cherenkov detectors represent a robust approach to study neutrino interactions, as it has been demonstrated by experiments such as Super-Kamiokande [15] or K2K [29]. While both LAr-TPC and water-Cherenkov technologies have strengths and weaknesses, the complementarity between their results is crucial. It is worth pointing out that, in order to compete with next-generation megaton-scale water Cherenkov detectors (dominated by Hyper-Kamiokande [35]), a LAr TPC should have a mass of $\mathcal{O}(100 \text{ kton})$.

An important aspect affecting the LAr TPC performance is the intrinsic presence of radioactive contaminants in the natural argon. Namely, the longest-lived radioactive isotopes are ^{39}Ar , ^{42}Ar and ^{37}Ar with a half-life of 269 years, 32.9 years y 35.04 days, respectively [71]. Their activities (beta decays) generate backgrounds that must be distinguished from the signal of interest. In particular, intrinsic contamination of ^{39}Ar in natural argon (leading to ~ 100 -keV events) is especially critical for direct dark matter searches (few of keV) and, hence, underground argon (UAr) is employed instead [78].

In order to achieve long electron drift distances, the LAr purity must be excellent since drift path is limited by the electron attachment to electronegative impurities in the medium. The electron lifetime measurement during the LAr TPC operation can provide an estimation of the contaminant concentration (O_2 equivalent). The ionization charge decreases exponentially with the drift time as:

$$Q(t) = Q_0 e^{-t/\tau} \quad (2.5)$$

being τ the mean electron lifetime in argon. Then:

$$\tau[\mu s] \approx \frac{300}{\rho[\text{ppb}]} \quad (2.6)$$

where ρ is the impurity concentration and ppb stands for parts-per-billion. Commercial LAr is contaminated by oxygen at a few ppm ($\text{ppm} = 10^{-6}$) level and, thus, only offers electron lifetimes of about $0.3 \mu s$ (less than 1 mm of drift). This is completely insufficient for a LAr TPC. As a solution, both purification of the LAr before the TPC filling and continuous purification of the LAr inside the cryostat through a dedicated purification system are carried out, allowing LAr purities levels bellow 0.1 ppb of O_2 equivalent ($\mathcal{O}(\text{ms})$ electron lifetimes corresponding to $\mathcal{O}(\text{m})$ attenuation lengths [79]).

Finally, LAr, as other liquified noble gases, is an excellent scintillator [80] and pure LAr is highly transparent to its own scintillation light. Further discussion on the light mechanisms in LAr can be found in Section 2.5.

2.4 Single-phase and dual-phase technologies

There are two main LAr TPC technologies: single-phase (SP), in which the detector is full of LAr; and dual-phase (DP), in which both liquid and gaseous argon are employed. Further information on both approaches will be given in the next chapter when the DUNE far detector design is discussed (Section 3.2.3). The key features of each technology are:

- In a SP LAr TPC (Figure 2.3), the electric field drifts the ionization charges in LAr towards an anode where they are collected. The anode plane is usually made up of three wire planes. A very low electronic noise is required in this configuration. This mature and robust technology, firstly tested in ICARUS [81], is used in Fermilab experiments of the short-baseline neutrino (SBN) program such as MicroBooNE [82]

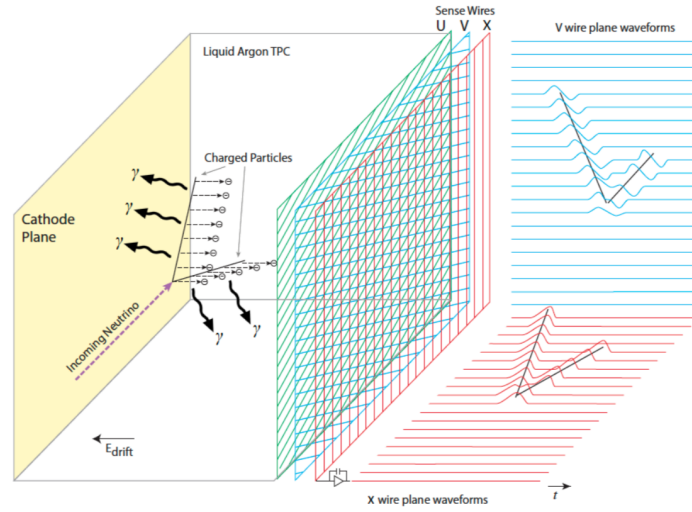


FIGURE 2.3: Operating principle of a single-phase LAr TPC. The light sensors (providing the event t_0) are not shown in the drawing. Figure taken from [34].

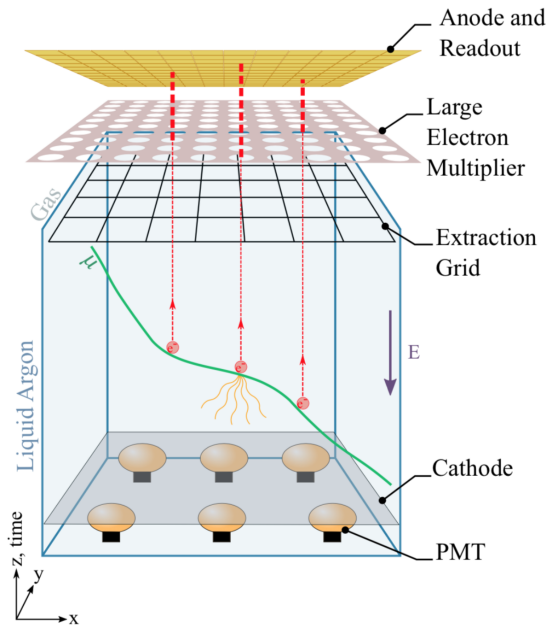


FIGURE 2.4: Operating principle of a dual-phase LAr TPC. Figure taken from [34].

(currently operating) and SBND [83] (under construction), as well as in detectors at the long-baseline neutrino facility (LBNF) such as the future DUNE [34] (see next chapter).

- The DP approach (Figure 2.4) was pioneered at the tonne scale by the WA105 demonstrator [84]. In the DP configuration, the ionization charges drift vertically in LAr towards a horizontal anode at the top. The main difference with respect to the SP concept is that, in the DP there is a layer of gaseous argon above the LAr volume, before the anode readout, in which the signal is amplified through a Townsend

avalanche. Thanks to this exclusive DP feature, longer drift lengths are achievable (thereby minimizing the nonactive materials in LAr) because the requirements on the electronic noise are reduced. The DP allows a single and homogeneous LAr volume but the electron extraction from liquid to gas requires an excellent control of the interface level. Some advantages that are pursued with the DP design are a fine readout pitch, a low energy threshold (motivating its use in dark matter detectors or for low-energy neutrino physics), a high signal-to-noise ratio over long drift distances and an excellent pattern reconstruction of the events. The lower number of elements needed inside the cryostat results in a reduction of both the intrinsic backgrounds and the cost.

The detection of the scintillation light produced in the argon is useful in both technologies. In the DP design there is not only prompt scintillation light production in LAr (the so-called S1 signal) but also a secondary light (S2) or electroluminescence signal in the gas phase. While the primary light is mainly used for the event trigger, valuable information such as the charge drift distance and track topology can be obtained from the analysis of the secondary light, as reported in [85, 86]. The next sections describe the scintillation light mechanisms in LAr and also extend the discussion on the light benefits in a LAr TPC.

It is important to comment that the SP TPC technology has been employed for both the detection of GeV-neutrinos and searches of keV-candidates of dark matter since the device was conceived. However, while in the former case the ionization density of, for example LAr, is high enough to allow a good detection without any signal multiplication (SP mode), the latter case involves very low-energy events and amplification is strongly beneficial (DP approach). Therefore, dark matter detectors, smaller in size than the neutrino ones, are usually DP and rely on the electroluminescence signal from the gas as well. Note that, in neutrino physics, the DP technology is more challenging as it requires longer electron drift lengths (due to the larger target volume) and the detection of the charge in the gas phase. As a consequence, the DP is still under development and, in fact, the recent R&D effort made with the ProtoDUNE-DP detector at CERN has motivated this thesis.

2.5 Scintillation light in LAr

2.5.1 Light production in LAr

LAr scintillation photons are emitted in a narrow band of 10 nm centered around 127 nm [76], in the Vacuum Ultra Violet (VUV) regime. The scintillation light production in LAr is explained in this section. The LAr light corresponds to the primary scintillation (S1) signal in a LAr TPC, both SP and DP. The mechanisms in condensed argon are similar to the ones for the gas argon phase in a DP LAr TPC, where additional light from electroluminescence provides a secondary light (S2) signal (see Section 2.5.4).

Excimer formation	Process	Reaction
Direct	Excitation	$e^- + Ar \rightarrow Ar^* + e^-$
	Excimer formation	$Ar^* + Ar \rightarrow Ar_2^{*,\nu}$
	Relaxation	$Ar_2^{*,\nu} + Ar \rightarrow Ar_2^* + Ar$
	VUV emission	$Ar_2^* \rightarrow Ar + Ar + \gamma$
From recombination	Ionization	$e^- + Ar \rightarrow Ar^+ + 2e^-$
	Recombination	$Ar^+ Ar + Ar \rightarrow Ar_2^+ + Ar$
		$e^- + Ar_2^+ \rightarrow Ar^{**} + Ar$
		$Ar^{**} + Ar \rightarrow Ar^* + Ar + \text{heat}$
		$Ar^* + Ar + Ar \rightarrow Ar_2^* + Ar + \text{heat}$
	VUV emission	$Ar_2^* \rightarrow Ar + Ar + \gamma$

TABLE 2.2: LAr scintillation light emission from excimers. The ν index indicates vibrational excitation.

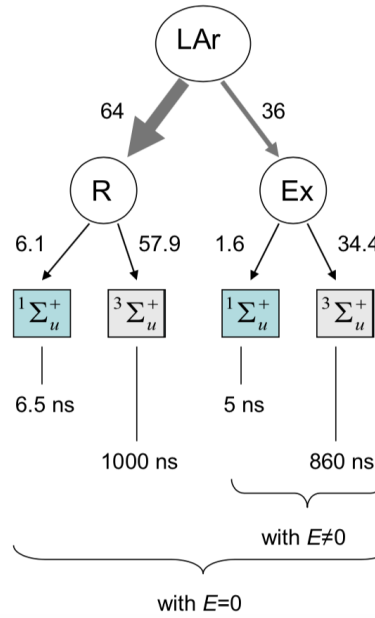


FIGURE 2.5: Observable distribution (percent) of the scintillation photons from fast electrons (0.5-1 MeV) in LAr. R and Ex indicate recombination and direct excitation channels, respectively. Figure taken from [93].

As stated in Equation 2.1, one ionizing particle passing through a LAr TPC creates free excitons and electron-ion pairs. Argon excitons and ions produce excited (Ar_2^*) or ionized (Ar_2^+) argon dimers, respectively. Ar_2^+ molecules eventually recombine with electrons to form Ar_2^* excimers, that then decay non-radiatively to the first singlet ($^1\Sigma_u^+$) and triplet ($^3\Sigma_u^+$) excited states. Then, VUV photons are emitted in the transition from these excited states to the ground state ($^1\Sigma_g^+$). The dissociation of the molecule occurs at short interatomic distances where the repulsive potential of the ground state allows the transition. The sequence up to the light emission is summarized in Table 2.2 within the group *direct excimer formation*. On the other hand, light production from the recombination

of electrons with positive ions formed shortly ($\sim$ ps) after ionization follows a different chain of processes, as it can be seen in Table 2.2 within the group *excimer formation from recombination*.

The decay times of the excited states are quite different in LAr despite being the de-excitation spectroscopically indistinguishable: $\tau_{fast} = (6 \pm 2)$ ns for the singlet and $\tau_{slow} = (1590 \pm 100)$ ns for the triplet [87]. The reason is that the transition from the triplet to the ground state (which is a singlet) is strongly suppressed and is possible only through spin-orbit coupling with much longer lifetime, $\mathcal{O}(\mu\text{s})$. Different decay time values can be found in the literature within the intervals $\tau_{fast} = (2 - 7)$ ns and $\tau_{slow} = (1020 - 1634)$ ns, as documented in [86], reference in which an extensive discussion of the time dependance of the scintillation light profile can be also found, including the estimation of an additional *intermediate* component, $\tau_{int} = (50.7 \pm 4.1)$ ns. Such a result is based on experimental light data collected in the WA105 demonstrator. Although the origin of the intermediate component has not been completely identified yet, it is found to be needed to fairly reproduce the observed scintillation time profile.

In addition, it has been observed that the time profile can be altered by doping of the LAr with noble gases like xenon [88]. In fact, the use of xenon-doped LAr is a promising alternative to pure LAr in large-scale detectors as it mitigates the light suppression due to impurities as well as it improves the detection efficiency and uniformity [89, 90].

The time for direct excimer formation is $\mathcal{O}(\text{ps})$ [91] while the recombination time is reported to be $\mathcal{O}(\text{ns})$ [92]. It is worth pointing out that the recombination in LAr involves complex mechanisms and a large number of factors. Consequently, the recombination dynamics is not completely understood yet. Details on the different recombination models that are proposed to explain the scintillation and ionization responses can be found in [64, 93].

Since the final reaction with VUV emission is similar in both chains of Table 2.2, the wavelength and decay times are similar. Nevertheless, different relative populations of singlet (6.1% vs. 1.6%) and triplet (57.9% vs. 34.4%) states are reached depending on the mechanism [93], as shown in Figure 2.5. In total, about 7.7% of the scintillation photons are emitted from singlet states and about 92.3% from triplet states. In the diagram of Figure 2.5, it is also indicated that, in absence of electric field, $\sim 2/3$ of the scintillation light comes from recombination whereas the remaining $\sim 1/3$ is due to direct excitation.

The so-called Birks' law [94] is a semi-empirical model that describes the light yield ($\mathcal{L}$) as a function of the drift field (ε) as:

$$\frac{\mathcal{L}(\varepsilon)}{\mathcal{L}(\varepsilon = 0)} = 1 - R \quad (2.7)$$

$$R = \frac{A}{1 + k \cdot (dE/dx)/\varepsilon} \quad (2.8)$$

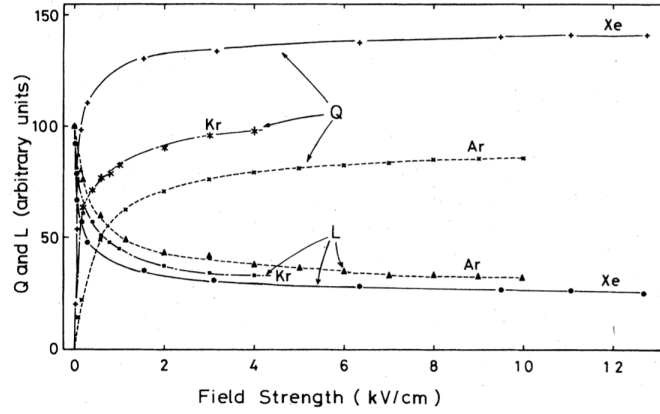


FIGURE 2.6: Variation of relative luminescence intensity L and collected charge Q in liquid argon, krypton, and xenon, as a function of the electric field for electrons of 0.976-1.05 MeV. Figure taken from [92].

where A and k are constants to be obtained from data fit, and dE/dx is the particle stopping power. The relation in Equation 2.7 is not linear at high loss rates. According to Birks' formula, recombination and quenching effects are two factors involved in the light yield. Both factors are briefly discussed below.

On the one hand, the impact of the electron-ion recombination can be evaluated in a LArTPC by measuring the light yield at different drift field strengths. Whereas full recombination takes place in absence of fields, certain suppression of the effect (and, thus, of the scintillation light emission) is expected at high field values, as it can be seen in Figure 2.6. For a drift field of about 6 kV/cm, 64% of scintillation decrease has been observed in LAr [92]. The investigation of the drift field impact on the light production in ProtoDUNE-DP LAr TPC is presented in this thesis, see Section 8.3.5.

On the other hand, the light quenching primarily occurs when the reaction $Ar^* + X \rightarrow 2Ar + X$, being X an electronegative impurity atom, prevents the excimer formation reaction, $Ar^* + Ar \rightarrow Ar_2^{*,\nu}$, displayed in Table 2.2. The destruction of excimer states is non-radiative. Reactions between the LAr impurities and Ar_2^* can also compete with the final de-excitation process, $Ar_2^* \rightarrow Ar + Ar + \gamma$, that leads to VUV emission. As a consequence, the LAr purity strongly affects the scintillation light production. The (impurity) quenching on the light yield is evident in the slow component of the light emission: the greater the LAr contamination, the shorter the triplet lifetime [90].

2.5.2 Light propagation in LAr

The probability of detecting the light generated at some point of the LAr volume decreases with the path travelled by the light since several optical phenomena contribute to a finite photon attenuation length [95]. The most-relevant factors affecting the propagation of the

scintillation light in LAr are described in this section: absorption and Rayleigh scattering. The inverse of the overall attenuation length can be expressed as:

$$\frac{1}{\lambda_{\text{Att}}} \approx \frac{1}{\lambda_{\text{Abs. LAr impurities}}} + \frac{1}{\lambda_{\text{Abs. materials}}} + \frac{1}{\lambda_{\text{Rayleigh}}} + \dots \quad (2.9)$$

where the first and second terms correspond to photon absorption by impurities in LAr and detector materials, respectively, and the third term stands for the Rayleigh scattering. Equation 2.9 is not written as a finite sum as other mechanisms can also affect indirectly to the attenuation of the light. Therefore, the separate determination of the attenuation components is difficult. For LAr, attenuation length values of 66 cm [96] and 52.1 cm [97] have been reported in the literature.

The loss of VUV photons due to absorption in a LAr TPC is related to: 1) the presence of photo-sensitive impurities in the LAr bulk such as traces of xenon [98], and 2) the absorptive materials in the detector. It is important to point out that self absorption in pure argon is negligible (it is fully transparent to its own scintillation light) [99]. Unlike the light yield quenching described in the previous section, the VUV-light absorption during its propagation in the LAr can not be evaluated in the scintillation profile. The reason is that it equally affects fast and slow components. Thus, the phenomenon must be investigated in terms of the attenuation length.

The Rayleigh scattering consists in the elastic scattering of electromagnetic radiation by particles much smaller than the wavelength of the radiation. This scattering process increases the distance photons travel between their production and detection and, thus, spreads the arrival time of the photons. The length that light can travel before undergoing Rayleigh scattering is the Rayleigh scattering length (RSL, previously called $\lambda_{\text{Rayleigh}}$ in Equation 2.9) and it depends on the light wavelength as well as on the optical properties of the medium. The inverse of the RSL can be expressed as (see the detailed derivation in [100]):

$$RSL^{-1} = \frac{16\pi^3}{6\lambda^4} \left[kT\rho\kappa_T \left(\frac{(n^2 - 1)(n^2 + 2)}{3} \right)^2 \right] \quad (2.10)$$

where λ is the light wavelength, k is the Boltzmann's constant, T is the temperature, ρ is the density, κ_T is the isothermal compressibility, and n is the refractive index. The Rayleigh scattering impact must be specially taken into account in large-size detectors.

A summary of the RSL values reported in the literature is given in Table 2.3. The tension among the RSL results suggests that further investigation towards a reference value is still needed. In this thesis, an study on the RSL value is performed by comparing the measured attenuation length from ProtoDUNE-DP light data with simulations where two RSL hypotheses are tested. Results will be presented in Section 8.3.6.

Despite Rayleigh scattering can make the optical reconstruction in a LAr TPC more complicated, the total amount of light can be nearly preserved inside the volume if the

Source	RSL value (cm)	Reference
Measurement	99.9 ± 0.8	[77]
Calculation	55 ± 5	[101]
	90	[102]
Simulation	46 ± 11	[103]

TABLE 2.3: RSL values reported in the literature and obtained from measurements, simulations or calculations.

detector materials have enough VUV reflectance (which is not a trivial). In a similar way, absorption by LAr impurities is identified as a problem that only the continuous LAr purification can mitigate.

2.5.3 Light detection in LAr

The VUV photon collection in a LAr TPC can be performed using different sensors. It must be taken into account that the cryogenic operation of the photon-detectors (PD) can cause an efficiency reduction with respect to their performance at room temperature. While photomultiplier tubes (PMTs) have been the default choice for light collection in LAr detectors for a long time, silicon photomultipliers (SiPM) (alone or either installed in light-guide bars or light traps) are chosen instead by some current experiments due to their low power consumption, low noise in cryogenic conditions and high quantum efficiency (up to 40% [104]). The particular case of PMT-based light detection in large LAr TPC detectors is the fundamental topic of this thesis and, thus, further information will be given over this document.

In the case of PD like PMTs which are primarily sensitive in the visible range, the installation of a wavelength shifter (WLS) material is required to absorb the VUV photons, shift them into the visible spectrum and re-emitted them. Typically, this is done with tetraphenyl butadiene (TPB). More details will be discussed in Section 4.8.4.

2.5.4 Electroluminescence light

As explained before, in a DP LAr TPC, apart from the prompt scintillation light (S1) signal produced in all LAr detectors, there is also a secondary scintillation (S2) or electroluminescence signal generated in the gas argon [105, 106] that is proportional to the drifted charge and to the amplification field strength. An important milestone to remark is that both the charge multiplication and the S2 detection were successfully accomplished in the DP demonstrator WA105 [85, 107, 86]. Examples of the scintillation light profiles (average waveforms) collected by the PMTs in WA105 with and without electroluminescence are displayed in Figure 2.7.

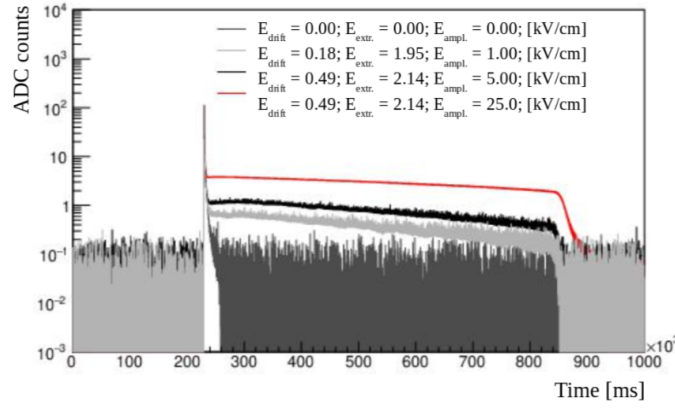


FIGURE 2.7: Average PMT waveforms collected in different field conditions (drift, extraction and amplification) in the WA105 demonstrator. Both the S1 (prompt) and S2 (secondary) signals are clearly visible. Figure taken from [86].

The photon production mechanisms in gas are similar to the ones described above for LAr. In the DP mode, the drifted electrons from ionization are extracted from LAr to the gas phase by means of a strong local electric field. Once in the gas, electrons are accelerated using an electric field to produce secondary ionizations or Townsend avalanches. In this way, they reach sufficient energy to also excite gas atoms and VUV photons are released in the eventual decays of the excimers.

The S2 light yield per cm (N_{ph}/dx) depends on the electric field strength (E in V/cm) as follows [105, 93]:

$$\frac{1}{n} \frac{N_{ph}}{dx} = a \frac{E}{n} - b \text{ [photons}\cdot\text{cm}^2/\text{e}] \quad (2.11)$$

where a and b are gas-specific empirical constants, and n is the number of rare gas atoms per cm^3 .

Two secondary effects to take into account are the photoelectric feedback caused by S2 photons [108] and the ions flowing back to LAr [109]. While the former can result in secondary avalanches altering the expected proportionality between amplified charge and S2 light, the latter can create inhomogeneities in the electric field pattern.

The S2 production delay with respect to the associated S1 signal is related to the electron path in LAr, which allows the determination of the electron drift velocity. In addition, relevant information on the event track topology can be extracted from the duration of the S2 signal. For instance, the more inclined the track is with respect to the photo-sensor, the larger the S2 time extension is.

2.6 Interest of the light in a LAr TPC

The light detection in a LAr TPC detector can be exploited with different purposes. Some of them are listed below:

- The prompt light signal allows the determination of the absolute event time (t_0) in the TPC, which is fundamental for the reconstruction of the interaction coordinate in the drift direction.
- The timing information can be employed to compensate the signal degradation with the drift distance, correct the energy measurement and, hence, improve the TPC resolution.
- The t_0 measurement is essential for the fiducialization of a LAr volume around an interaction point in the search for rare events such as nucleon decay. The light collection also allows a significant background reduction in these analyses.
- A light-based trigger system for supernova neutrino burst detection can be developed independently of the charge-based trigger. This redundancy is considered to be fundamental, given the rarity of a core-collapse supernova.
- Calorimetric studies as well as particle identification can be performed with light data and complement the results from the charge analysis.
- The combination of the charge readout and the photon collection enhances the overall detecting capabilities.
- The LAr purity stability, crucial for a good TPC performance, can be quantitatively controlled through the measurement of the slow component from the scintillation light time profile.
- In the case of a DP detector, the secondary signal (S2) from the gas phase is proportional to the drifted charge and is collected with a certain delay with respect to the prompt signal (S1) from LAr. The S2 lasts until the farthest electrons reach the extraction region and, hence its duration is comparable to the maximum electron drift time. Exclusive and valuable information can be obtained from the S2 analysis on the charge signal, the electron drift velocity, the track topology, the LAr purity level, etc. These advantages are exploited in both dark matter and neutrino experiments, being the S2 detection more challenging in the case of neutrino detectors, in which the sensitive volume tends to be larger and the electroluminescence occurs farther from the light detectors.

For the reasons above, the photon detection plays a key role in a LAr TPC, as it will be remarked over this dissertation.

Deep Underground Neutrino Experiment

“Coming together is a beginning,
staying together is progress,
and working together is success.

— Henry Ford

3.1 Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-baseline (LBL) neutrino oscillation experiment that aims to deliver world-leading results in neutrino physics and astrophysics in the next decades [34, 110, 111, 112, 113]. DUNE is a dual-site experiment that will consist of a near detector (ND) located at Fermilab in Illinois, USA, where the muon-neutrino beam of the Long-Baseline Neutrino Facility (LBNF) is produced, and an underground far detector (FD) with four 10-kt fiducial mass liquid-argon (LAr) time-projection chambers (TPCs) at the Sanford Underground Research Laboratory (SURF) in South Dakota, USA, 1300 km downstream the source. The FD of DUNE, with a total mass of 68 kt of LAr, will be the largest of its type ever built.

The main physics goal of DUNE is to precisely measure all the parameters that govern the neutrino mixing towards the definitive discrimination of the neutrino mass ordering, the measurement of the charge-parity (CP) violation phase and the determination of the θ_{23} octant. These significant aspects will be explored in a single experiment thanks to the exceptional potential of the DUNE design, which will count on a 1300-km oscillation baseline through Earth as well as a powerful neutrino (antineutrino) beam, both fundamental to explore the mass ordering and CP-phase problems simultaneously through the study of matter effects. See the probabilities of neutrino oscillations through matter in Figure 3.1. The experiment layout will allow robust oscillation measurements over a range of energies spanning the first and second oscillation maxima. In addition, the deep underground location of the FD reduces cosmogenic and atmospheric backgrounds and, as a result, its broad science program also addresses non-beam physics such as nucleon decay searches and the measurement of the neutrino flux from a galactic core-collapse supernova.

The DUNE collaboration is an international organization made up of over 1300 collaborators from over 200 institutions in over 30 countries plus the European research center CERN. DUNE was formed in April 2015 from the fusion of Long Baseline Neutrino

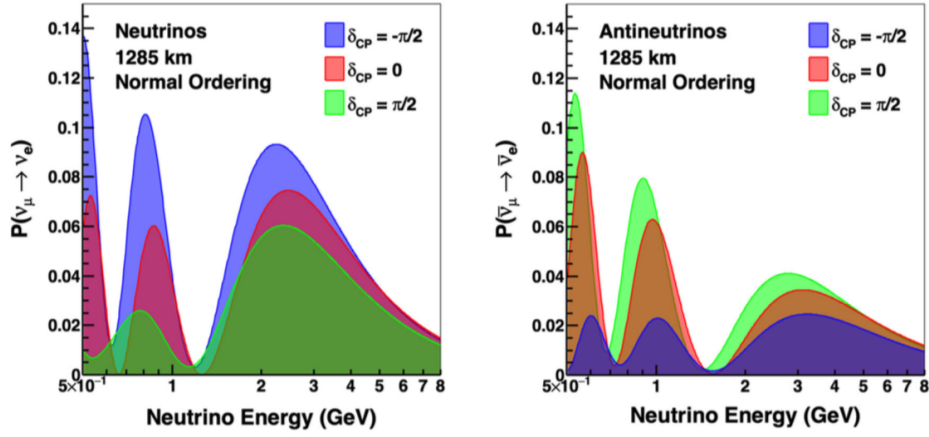


FIGURE 3.1: Appearance probability at a 1285-km baseline as a function of neutrino energy in DUNE, for different values of δ_{CP} , for neutrinos (left) and antineutrinos (right), assuming standard three-flavor model, normal ordering and a constant density approximation [37].

Experiment (LBNE) in USA, Long Baseline Neutrino Observatory (LBNO) in Europe and new international partners.

An overview of the DUNE experiment is presented in this chapter. Firstly, the experimental setup of DUNE is described in Section 3.2. Next, Section 3.3 summarizes the R&D effort carried out at the CERN Neutrino Platform focusing on the development of detector prototypes towards the DUNE FD modules. Lastly, the ambitious physics program pursued by the experiment is summarized in Section 3.4.

3.2 DUNE experimental configuration

Figure 3.2 illustrates the basic experimental setup of DUNE. It comprises the LBNF neutrino beam at the Fermilab accelerator complex, a ND located just downstream the neutrino source and a massive FD 1.5 km underground at SURF, 1300 km away. Both ND and FD are placed in an on-axis configuration to receive the neutrino beam.

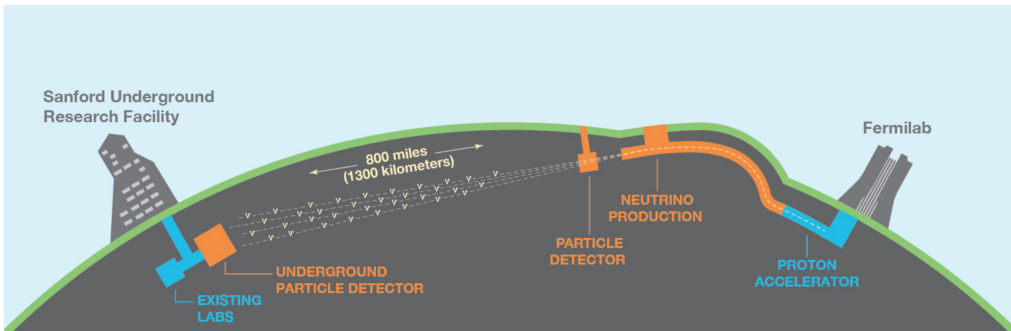


FIGURE 3.2: Diagram of the Deep Underground Neutrino Experiment layout [34].

The DUNE FD installation is expected to start in 2024. The DUNE project will follow an staged deployment plan [34]:

- Start of beam run: two FD modules (20 kt fiducial mass in total) and 1.2-MW beam.
- After one year: add one FD module (30 kt fiducial mass in total).
- After three years: add one FD module (40 kt fiducial mass in total).
- After six years: upgrade to 2.4-MW beam.

3.2.1 Neutrino beam

The neutrino beam at Fermilab (Figure 3.3) is designed to be the most intense in the world [34, 110]. A powerful proton beam from Fermilab Main Injector (MI) in the energy range 60 GeV to 120 GeV will deliver between 1.0 MW and 1.2 MW to LBNF. A further upgrade of Proton Improvement Plan-II (PIP-II) will enable it to provide up to 2.4 MW of beam power by 2030. After aiming and focusing the proton beam, it will collide with a target area of graphite to produce a secondary beam of charged particles later focused on a magnetic

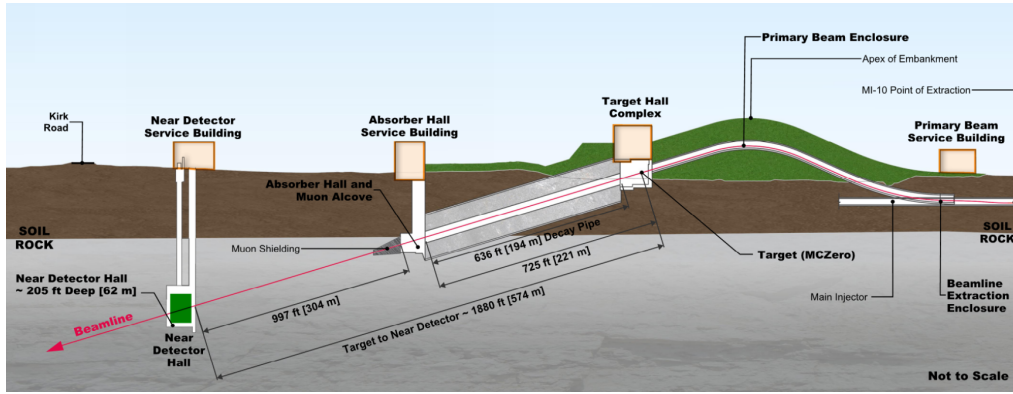


FIGURE 3.3: Schematic of the DUNE beamline and the ND hall at Fermilab [34].

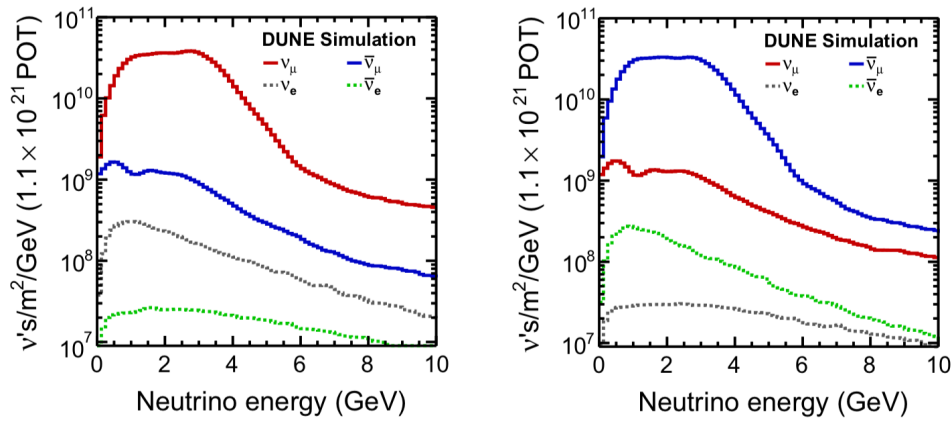


FIGURE 3.4: Neutrino fluxes at DUNE FD for neutrino-enhanced (left) and antineutrino-enhanced (right) beam running [37].

horn system. The intense neutrino flux (0.5 GeV to 8.0 GeV) emerge from the decay of pions and kaons in a dedicated decay pipe with helium and a hadron absorber. Either neutrino-enhanced or antineutrino-enhanced beams are created by operating the focusing horns in forward or reverse current configurations, respectively. Most of the neutrinos of the beam are muon-type, as it can be seen in Figure 3.4, where expected the composition of the neutrino (antineutrino) flux at the FD is shown.

3.2.2 Near detector

The DUNE ND [114], located 574 m far away from the neutrino production point, is crucial to measure the initial unoscillated neutrino (antineutrino) beam flux and determine its flavor composition. In addition, the ND is key to reduce the systematic uncertainties in the neutrino flux to the level required to discover CP (charge-parity) violation. The composite (*i.e.*, multi-purpose) ND also has a rich program of its own on the study of neutrino interactions with both liquid and gaseous argon. This program will include precise neutrino cross-section measurements, nuclear effect studies, and beyond the standard model (BSM) physics.

The ND comprises three primary detectors, see Figure 3.5, that provide complementary information:

- ND-LAr: formed of 35 optically separated LAr TPC modules (ArgonCube structure [115]) to measure the initial neutrino flux with several techniques. It is the most similar to FD. Each TPC has a high-voltage cathode, a field cage, a light collection system, and a pixel-based charge readout.
- Multi-purpose detector (MPD) or ND-GAr: a high-pressure gaseous argon TPC surrounded by an electromagnetic calorimeter (ECAL) and a 0.5-T magnet. It is used to measure the momentum and charge of the particles exiting ND-LAr and, thus, to determine the energy of the incoming neutrino. It has a lower energy threshold than ND-LAr.

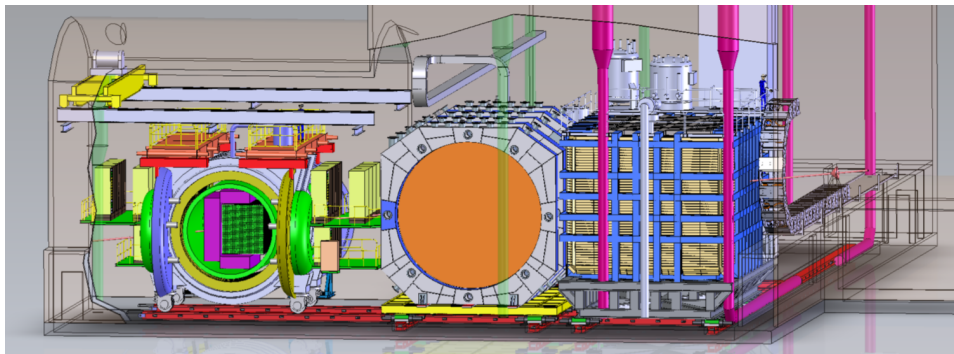


FIGURE 3.5: Diagram of the DUNE ND hall [114]. The three detectors (ND-LAr, MPD and SAND) are displayed from right to left.

- System for on-Axis Neutrino Detection (SAND): an on-axis beam monitor, surrounded by an ECAL and a 0.6-T magnet. The inner volume of the magnet and ECAL are instrumented with a target/tracking system. SAND measures the sign and momentum of particles and can provide particle identification by dE/dx .

The first two detectors can be moved sideways up to 33 m (off-axis configuration). This additional degree of freedom results in a drop of the neutrino flux mean energy and a more-monochromatic spectrum. Thanks to the possibility to take off-axis measurements, degenerate effects due to systematic biases of the energy reconstruction can be disentangled in the ND-FD comparison.

3.2.3 Far Detector

The DUNE FD [111] is foreseen to employ 40 kt of LAr (fiducial mass) split into four LAr TPCs with a modular design. A temperature of 88 K (-185 C°) is required to maintain the argon in liquid state using cryogenic systems. The two caverns housing the four FD modules are being excavated approximately 1.5 km underground at SURF. Given the huge dimensions of the DUNE FD modules, a modular design is followed in order to make the procurement, assembly and installation easier and faster. The FD will provide an unprecedented resolution to reconstruct neutrino interactions and will enable to develop a rich physics program (see Section 3.4).

Initially, two LAr TPC technologies were envisioned for the FD modules: 1) single-phase (SP), with all detector elements immersed in LAr, and 2) dual-phase (DP), relying on LAr but also on a layer of gaseous argon above the liquid. Nonetheless, the results from the prototyping phase (ProtoDUNE program at CERN, see Section 3.3) have modified the FD strategy and the challenging DP technology in its current state of development has been recently discarded for DUNE. The first DUNE FD module will employ the SP technology.

	SP FD [112]	DP FD [113]	VD FD [116]	
Feature	Value			Units
Technology	SP	DP	SP	–
Electron drift	Horizontal	Vertical	Vertical	–
Cryostat inner size	15.1×14.0×62.0	15.1×14.0×62.0	15.1×14.0×62.0	m ³
Active volume	12.0×14.0×58.2	12.0×12.0×60.0	13.0×13.5×60.0	m ³
Active LAr mass	10.0	12.1	14.7	kt
Total LAr mass	17.5	17.5	17.0	kt
High voltage	180	600	325	kV
Nom. drift field	0.5	0.5	0.5	kV/cm
Max. drift length	3.5	12.0	6.5	m
# CR* channels	384000	153600	512000	–
# Photon-detectors	1500 ARAPUCAs	720 PMTs	640 ARAPUCAs	–

TABLE 3.1: Features of a 10-kt DUNE FD module. Different technologies are compared. *CR: charge readout.

The design of the remaining three LAr TPC modules is open. An alternative approach known as vertical-drift (VD) is the evolution of the DP and is being considered for one of the next modules. Hence, a prototype to demonstrate the viability of the design is currently under development at CERN.

Despite the change of strategy, the huge R&D effort made to demonstrate the viability of the challenging but advantageous DP technology at the large scale (that is, WA105 [84] and ProtoDUNE-DP [113] detectors at CERN) is a valuable experience towards future detectors. This is the point of this thesis, which is focused on ProtoDUNE-DP.

The three aforementioned options for DUNE FD are briefly described in the following sections. Note that only the general features of each FD proposal are commented since details on the basic principles of each LAr TPC design can be found in Section 2.2. A summary of some characteristics of the proposed FD designs is given in Table 3.1.

3.2.3.1 First single-phase FD module

The configuration of the first SP FD module [112] can be seen in Figure 3.6. The detector, with 10 kt of active LAr mass, is divided into four drift volumes allowing a maximum drift length of 3.5 m. The two cathode walls are called cathode plane assembly (CPA) arrays. Each CPA array contains 150 $1.2 \times 4.0\text{-m}^2$ CPAs. The cathode is biased at -180 kV to produce a electric field of 0.5 kV/cm that drifts the electrons horizontally towards the anode. There are three anode walls formed of 50 $6.0 \times 2.3\text{-m}^2$ anode plane assemblies (APAs) with three layers of active wires each. Cold electronics (CE) are employed for the readout.

The collection of scintillation photons is performed by X-ARAPUCAs [117], novel devices based on silicon photomultipliers (SiPMs) that have been developed within the DUNE project. They consist of layers of dichroic filter and wavelength-shifter (WLS).

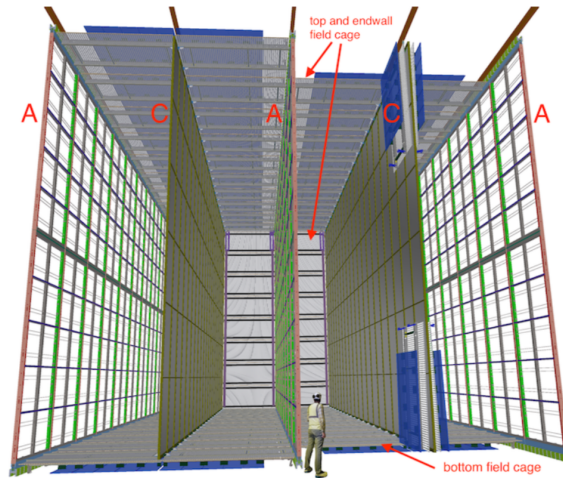


FIGURE 3.6: Configuration of a 10-kt DUNE SP FD module [112]. (A) and (C) refer to anode and cathode planes, respectively.

The converted visible photons are trapped and transported to SiPMs. The X-ARAPUCAs are installed through slots in the APA frame, in between the two sets of wire layers (10 ARAPUCAs per APA, 1500 per SP module).

3.2.3.2 Proposed dual-phase FD module

Besides the advantages already described in Section 2.4 when discussing the DP technology basics, the proposed DP DUNE FD design [113] has other distinctive features such as a finer readout pitch in two identical collection views, fewer readout channels, simpler underground construction and installation, and full accessibility and replaceability of the front-end electronics. In this configuration, it is possible to have a large homogeneous fiducial volume without embedded passive materials. In addition, as the number of components to be installed with respect to SP is lower, the overall cost is also lower.

The DP module (Figure 3.7) is built as a single active volume (12.1 kt of LAr) surrounded by the field cage. It corresponds to a maximum drift distance of 12 m. The anode is at the top, the cathode is near the bottom, and a photomultiplier tube (PMT) array is placed underneath the cathode. The cathode plane consists of 15 adjacent $4 \times 12\text{-m}^2$ modules of stainless-steel tubes suspended from the field cage. The ionization charges drift vertically in LAr thanks to the electric field of 0.5 kV/cm (-600 kV at the cathode) within the drift volume. Electrons drift upwards towards the anode plane at the top ($12 \times 60\text{-m}^2$), made of 80 $3 \times 3\text{-m}^2$ independent charge readout plane (CRP) modules with Large Electron Multiplier (LEM) devices for the electron avalanche. The CRPs allow a tunable amplification as well as the charge collection on two independent views in 3-m strips with 3.1-mm pitch. The vertical position of each CRP unit at the liquid-gas interface can be adjusted using three suspension feedthroughs. The cryogenic front-end electronics are installed in the signal feedthrough chimneys on the roof.

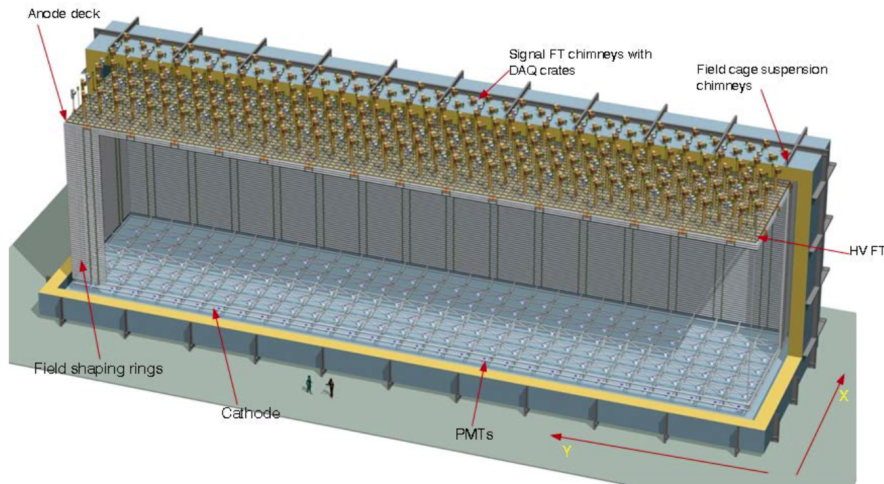


FIGURE 3.7: Main components of a 10-kt DUNE DP FD module [34].

Photon detection system The photon detection system (PDS) of the DP FD [113, 118] is formed of 720 PMTs from Hamamatsu Photonics (model R5912-MOD20) distributed uniformly on the floor of the cryostat ($1/\text{m}^2$). The selected PMT model has a diameter of 20 cm (8 inch), 14 stages of amplification and a high nominal gain (10^9 at room temperature). Its maximum quantum efficiency is about 20% at 400 nm. PMTs are a low-cost, large-area, efficient option for light collection in giant detectors. Each PMT has a thin layer of tetraphenyl butadiene (TPB) coating evaporated directly on its surface to shift the VUV light into visible photons. The same photosensor model was successfully operated in ProtoDUNE-DP [90] as well as in other LAr experiments such as WA105 [85], MicroBooNE [119] and ICARUS [120].

A positive biased base with a single cable for both high voltage (HV) and signal transmission reduces the required number of feedthroughs: the positive HV is supplied to the PMT anode while the photocathode is grounded. An external circuit per PMT is located outside the cryostat to separate the PMT and HV signals. The PDS includes a dedicated LED-driven fiber calibration system to determine the PMT gain and monitor the stability of the PMT response. Note that the light calibration system proposed for DUNE-DP corresponds to 20 modules as the successfully operated calibration system of ProtoDUNE-DP [151, 90].

A system of TPB-coated reflector/WLS panels integrated on the top half of the field cage inner walls allows the enhancement of the light collection as well as the improvement of the PDS response uniformity throughout the entire TPC active volume. The reflector/WLS panels are constructed with 1-mm thick, $93 \times 93\text{-cm}^2$ G10/FR-4 plates. One side of the panel is laminated with a reflective foil, which is then evaporated with TPB. This design is found to be suitable since the TPB coating on the PMT windows has 90% transmittance at 425 nm (emission peak of TPB).

3.2.3.3 Vertical-drift concept

The experience gained with ProtoDUNE (see next section) opens new possibilities for the second DUNE FD. The recent vertical-drift (VD) concept [116, 121], illustrated in Figure 3.8, is the evolution of the DP design, and is being considered for a FD module. This option combines the best features of the SP and DP detectors into a new LAr TPC technology. The VD detector operates in SP mode (only LAr) with the electron drift along the vertical axis. It is important to remark that specifications on the VD configuration are still preliminary as its conceptual design report is still in preparation. The VD development program foresees a demonstrator in 2021 and a full-scale prototype in 2023.

In the VD, two separate 6.5-m drift volumes are defined by a hanging cathode plane at mid height in the LAr: free electrons above the cathode drift upwards whereas the ones below the cathode drift downwards. A field cage constrains the electric field (0.5 kV/cm) to be uniform. The absence of amplification is compensated by: 1) the difference in the strips width, 2) the absence of the efficiency factor in the electron collection, and 3) the

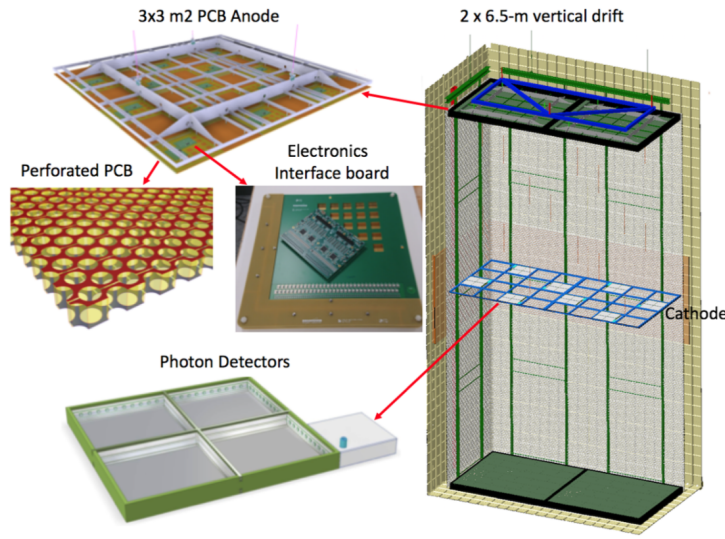


FIGURE 3.8: Schematics of the next-generation LAr TPC concept called vertical-drift [116].

collection of the electrons by a single view. As a result, the readout signal gets increased for the VD by a factor 5.3 with respect to the DP design at unit gain.

Printed circuit boards (PCBs) are used in the VD for the charge readout, as in the DP CRPs, but with strips on both faces. Thanks to this approach, the usual SP configuration of multiple wire layers is discarded and the anode plane assembly gets simpler and cheaper. The two anode planes (at top and bottom of the TPC), fully immersed in LAr, are formed of 80 $3 \times 3.375\text{-m}^2$ PCB-based CRPs each. Only ~ 1 kV across CRPs must be applied (vs. up to ~ 7 kV needed in the DP configuration) and, hence, risks due to sparks causing long term deterioration are removed. Furthermore, the status of the LAr surface, the presence of bubbles, and the floating dust and contaminants (major issues faced during the DP operation) are aspects that no longer affect the TPC operation.

The photon detection system for the VD is based on X-ARAPUCA [117] devices similar to the ones developed for the SP module. The ARAPUCA tiles are integrated in the cathode structure and behind the field cage onto the cryostat walls for a $\sim 4\pi$ coverage and nearly uniform light yield over the detection volume.

3.3 R&D program at the CERN Neutrino Platform

The ProtoDUNE detectors are two FD prototypes operated at the CERN Neutrino Platform as part of an R&D program towards DUNE [122, 123]. Their main purpose is to gain experience in building and operating large-scale LAr TPCs. Both detectors have similar sizes (about 1/20 of a FD module) and are located in an extension to the EHN1 hall in CERN's North Area, where they can be served by two Very Low Energy (VLE) charged-particle beamlines, H2 and H4, of the CERN Super Proton Synchrotron (SPS). See a picture of the detectors in Figure 3.9.

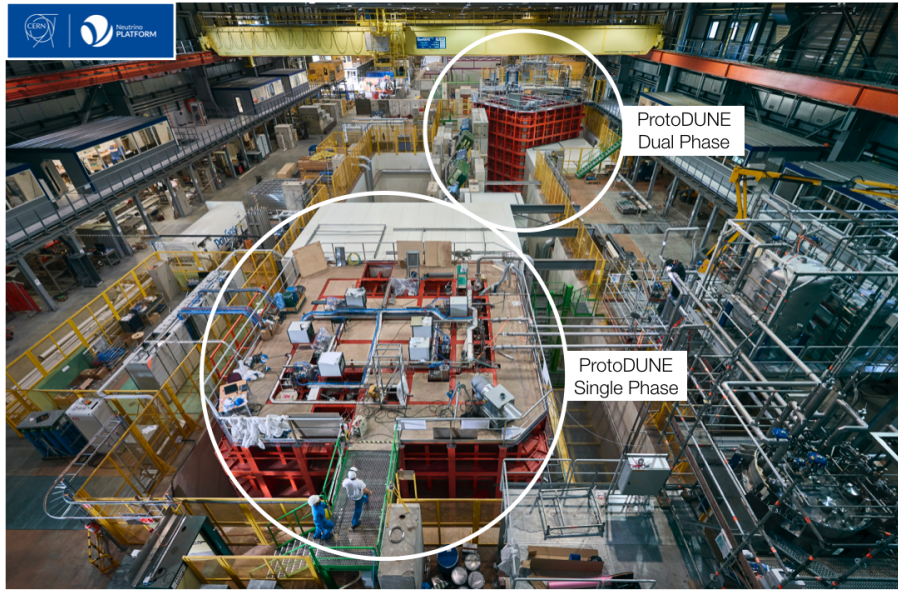


FIGURE 3.9: Picture of the CERN Neutrino Platform: R&D facility located in a test-beam hall at the Prévessin site. Both ProtoDUNE detectors can be seen.

Parameter	Value			Units
	ProtoDUNE-SP [125]	ProtoDUNE-DP [124]	WA105 [84]	
Technology	SP	DP	DP	–
Electron drift	Horizontal	Vertical	Vertical	–
Cryostat inner size	$8.5 \times 7.9 \times 8.5$	$8.5 \times 7.9 \times 8.5$	$4.8 \times 2.0 \times 2.4$	m^3
Active volume	$6 \times 7 \times 7$	$6 \times 6 \times 6$	$3 \times 3 \times 1$	m^3
Active LAr mass	411	300	4.2	t
Total LAr mass	770	750	24	t
High voltage	180	300	56.5	kV
Nom. drift field	0.5	0.5	0.5	kV/cm
Max. drift length	3.5	6.0	1.0	m
# CR* channels	15360	15360	1280	–
# PDs*	60 op. modules	36 PMTs	5 PMTs	–

TABLE 3.2: Basic features of the ProtoDUNE detectors and the WA105 demonstrator.

Apart from the validation of the technologies at the massive scale, the ProtoDUNE project aims to:

- Validate the DUNE FD design: elements in the 1:1 scale, test of the production and installation procedures, demonstration of long-term operational stability, etc.
- Collect test beam data with the H4 beamline (p , e^+ , π^+ , K^+ in the 0.3-0.7 GeV momentum range) to develop reconstruction techniques with real data, study the detector response (calibration, particle identification with dE/dx , energy resolution, etc.), and perform cross-section measurements of hadrons in argon.

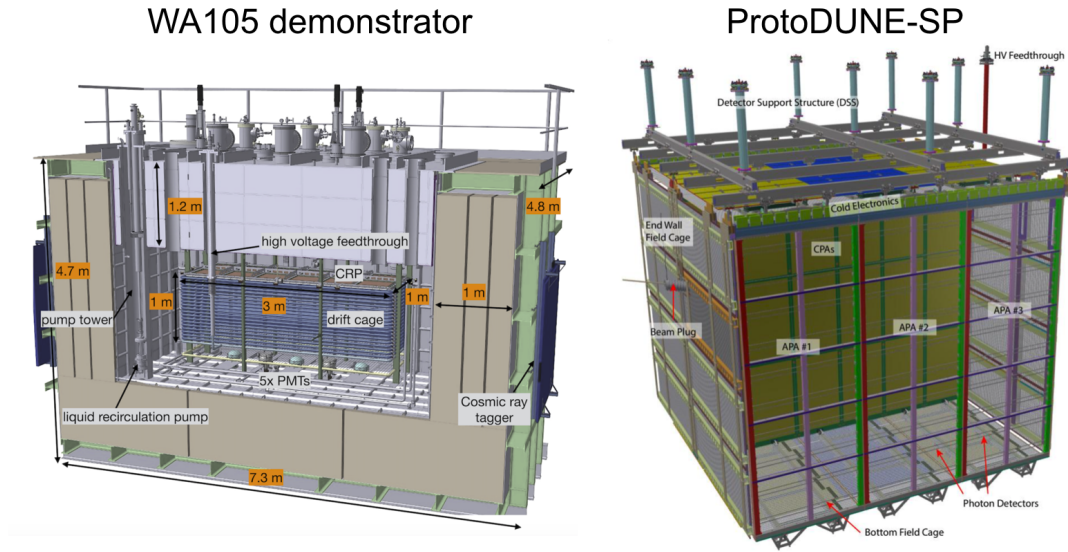


FIGURE 3.10: Schematic views of the WA105 demonstrator [84] (left) and the ProtoDUNE-SP detector [127] (right).

- Collect cosmic ray data to study the full detector response accounting for space-charge effects, test different field configurations, validate the LAr purification system and accomplish physics measurements such as the seasonal variation of the cosmic ray rate.
- Test the data acquisition, storage, processing and analysis framework for DUNE FD.

On the one hand, ProtoDUNE Single Phase (ProtoDUNE-SP) employs SP technology and has the same 3.5-m maximum drift length as the full SP module. On the other hand, ProtoDUNE Dual Phase (ProtoDUNE-DP) is a DP LAr TPC and has a 6-m drift, half of the proposed for the DP module. A detailed description of the ProtoDUNE-DP design can be found in Chapter 4 whereas the detector performance is the topic of Chapter 6. Therefore, no further information on ProtoDUNE-DP is given in this section. Some basic features comparing DUNE prototypes can be seen in Table 3.2, including the WA105 demonstrator.

WA105 [84], also known as the $3 \times 1 \times 1\text{-m}^3$ detector, was developed within the LAGUNA-LBNO European program [126]. It was a 4.2-t DP LAr TPC built and successfully operated at CERN as previous step to ProtoDUNE-DP. The WA105 design (see Figure 3.10 left) includes an anode plane at the top of the field cage and a cathode plane at the bottom, leading to a vertical electric field of 0.5 kV/cm. The charge extraction, amplification by LEMs and readout are done over an area of 3 m^2 , and there are 5 PMTs (Hamamatsu R5912-MOD20) installed on the cryostat floor for the light detection.

The WA105 demonstrator recorded cosmic-ray data in 2017. Results from its performance can be found in [85, 86, 107]. Although limitations on the high voltage prevented reaching the expected amplification, various milestones were achieved. For instance, the WA105 detector validated the concept of a non-evacuated industrial cryostat and

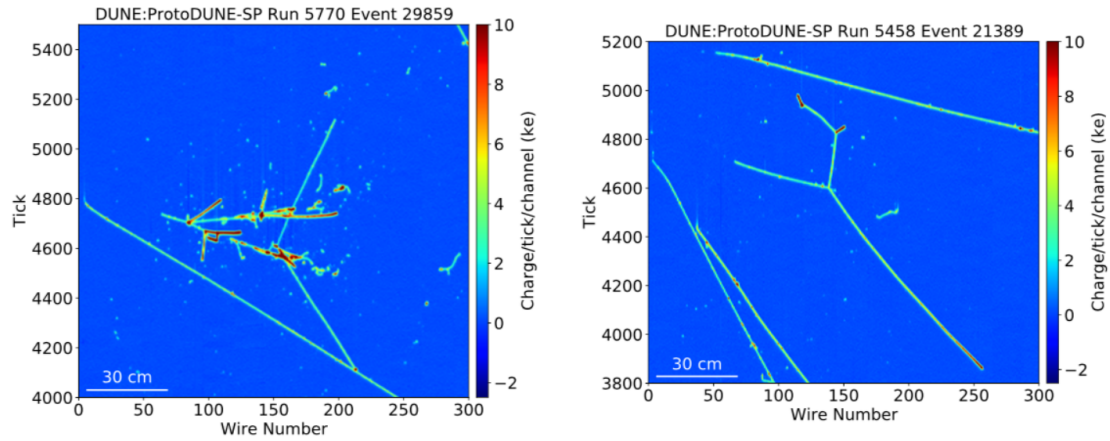


FIGURE 3.11: Candidate events from ProtoDUNE-SP data (beam particles entering from the left): 6-GeV/c kaon candidate (left) and 1-GeV pion candidate (right). The y-axis is the time in tick ($0.5 \mu\text{s}$) units. The color scale corresponds to the charge deposition. Figure from [68].

demonstrated for the first time the capabilities of DP technology at the tonne scale. The extraction of electrons from liquid to the gas phase in a 3-m^2 area was proven. In addition, the reached LAr purity was excellent, equivalent to an electron lifetime of 7 ms, and stable over time.

Concerning ProtoDUNE-SP [125, 127], it is a SP LAr TPC with an active LAr mass of ~ 411 t constrained by a field cage. The detector design (see Figure 3.10 right) consists of two vertical anode planes (made of 3 APAs each) with three planes of readout wires on both faces, and one vertical cathode plane (made of 18 CPAs). Thus, the ionization electron drift is horizontal through an electric field of 0.5 kV/cm . The PDS comprises 60 optical modules integrated in the APA frames (10 per APA) and three designs are deployed: two modules based on the ARAPUCA photon collection technology, 29 with dip-coated light guides and 29 with double-shift light guides. As WLS, the first two options use TPB while the ARAPUCA design employs p-terphenyl (PTP).

ProtoDUNE-SP collected hadron beam and cosmic ray data during the fall of 2018 (see event candidates in Figure 3.11), and then it took cosmic ray data until July 2020. A technical upgrade of the detector is ongoing for a second run of data taking with beam in 2022 (Phase II). The first ProtoDUNE-SP performance results are presented in [68]. The overall operation was a great success since the main performance parameters meet or exceed the DUNE FD specifications. For instance, the electric field was stable at the nominal level (500 V/cm), the measured electron lifetime in LAr was >20 ms, and the TPC and cold electronics show excellent signal-to-noise level (for example, 40.3 for the collection wires). Concerning the photon detection, the ARAPUCA technology showed 2% efficiency (expected light yield of 1.9 photons per MeV), the highest among the three tested optical designs. All these promising results encourage the development of massive LAr TPCs with SP technology, as the first DUNE FD module.

3.4 DUNE physics program

The primary science program of DUNE aims to address the following aspects [37]:

- **LBL neutrino (and antineutrino) oscillation measurements** leading to study the neutrino mass ordering (Δm_{13}^2 sign), the octant of the mixing angle θ_{23} , and the CP phase. More details in Section 3.4.1.
- **Proton decay searches**, a phenomenon of BSM physics and predicted by grand unified theories (GUTs) [128]. In DUNE, nucleon decay searches will be carried out in the $p \rightarrow K^+ \bar{\nu}$ decay channel as the LAr TPC technology allows the identification of the kaon (typically below the threshold in a water Cherenkov detector) by its distinctive dE/dx and decay signatures.
- **Measurement of the electron neutrino flux from a galactic core-collapse supernova**. Such a detection will provide unique information on the dynamics of a supernova explosion as well as on the possible birth signature of a black hole. More details in Section 3.4.2.

The ancillary program includes:

- **Other accelerator-based BSM physics studies:** non-standard interactions (NSIs); charge, parity, and time reversal symmetry (CPT) violation; sterile neutrinos; Lorentz invariance violation; large extra dimensions; heavy neutral leptons; and tests of tau neutrino appearance.
- **Study of atmospheric neutrino oscillations.**
- **Dark matter searches and non-accelerator-based BSM physics** such as neutron-antineutron oscillation.
- **Study of neutrino interactions in the DUNE ND**, including precise cross-section measurements and study of nuclear effects.

Studies on very low-energy events from other astrophysical sources such as solar neutrinos or the diffuse supernova neutrino flux¹ will be possible in DUNE only if the LArTPC technology advances in the next years and, thus, larger sensitivities are achieved.

DUNE sensitivities within the LBL neutrino oscillation program as well as the unique opportunities on supernova neutrino studies with DUNE are discussed in the next sections. In most of cases, the reached sensitivity will be constraint by the amount of collected data, which will depend, in turn, on the operating time according to the staged deployment scenario explained in Section 3.2.

3.4.1 Long-baseline neutrino oscillations

Thanks to measurement of the neutrino (antineutrino) oscillation patterns from ND to FD ($\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$), DUNE will precisely determine key parameters that govern

¹Flux of neutrinos and antineutrinos emitted by all core-collapse supernovae that have occurred so far in the Universe.

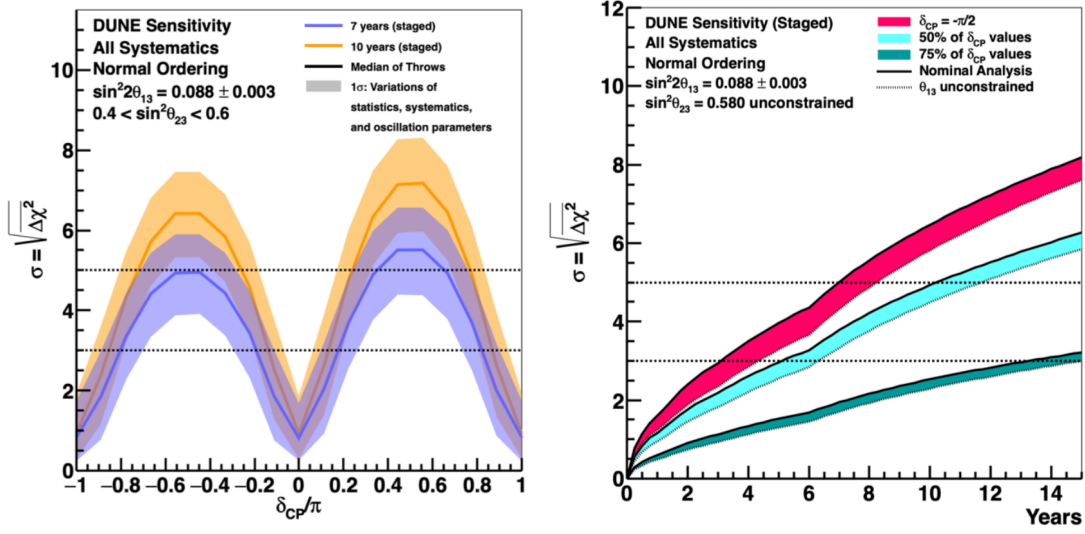


FIGURE 3.12: Significance of the CP violation discovery by DUNE [37]. Left panel: Significance as a function of the true value of δ_{CP} , for seven and ten years of exposure. Right panel: Significance for the case when $\delta_{CP} = -\pi/2$, and for 50% and 75% of possible true δ_{CP} values, as a function of time.

LBL neutrino oscillations, including δ_{CP} , $\sin^2 2\theta_{13}$, Δm_{13}^2 and $\sin^2 \theta_{23}$. The rich program of neutrino oscillations primarily aims at: 1) measuring the CP phase, 2) determining the neutrino mass ordering, and 3) measuring the octant of the mixing angle θ_{23} . The results presented in the following correspond to dedicated studies of DUNE sensitivity to neutrino oscillation. They are based on a full simulation, reconstruction, and event selection, including the uncertainties due to the flux prediction, neutrino interaction model, and detector effects.

The CP violation (*i.e.*, $\delta_{CP} \neq 0$ or π), already observed in kaons and B mesons, will be potentially discovered for the neutrino sector in DUNE with $>3\sigma$ ($>5\sigma$) evidence for $\delta_{CP} = -\pi/2$ after five (eight) years of operation and 50% of the δ_{CP} values will be excluded by 3σ after six years [37]. Figure 3.12 left shows the significance for CP violation determination as a function of the true value of δ_{CP} for seven and ten years of data. In Figure 3.12 right, the significance for CP violation discovery as a function of exposure time is presented. The key for this discovery, which will help to understand the matter-antimatter asymmetry in the universe, relies on the differences in the propagation through matter of neutrinos and antineutrinos.

Figure 3.13 displays the significance for the determination of the neutrino mass ordering (sign of Δm_{31}^2) by DUNE as a function of the value of δ_{CP} (left) and as a function of time (right). According to the sensitivity results, DUNE will be able to establish the neutrino mass ordering at the $5\text{-}\sigma$ level for 100% of δ_{CP} values after between two and three years of operation.

Finally, the value of $\sin^2 \theta_{23}$ will be assessed in DUNE through the combination of both ν_e appearance and ν_μ disappearance measurements. Both maximal mixing and the θ_{23}

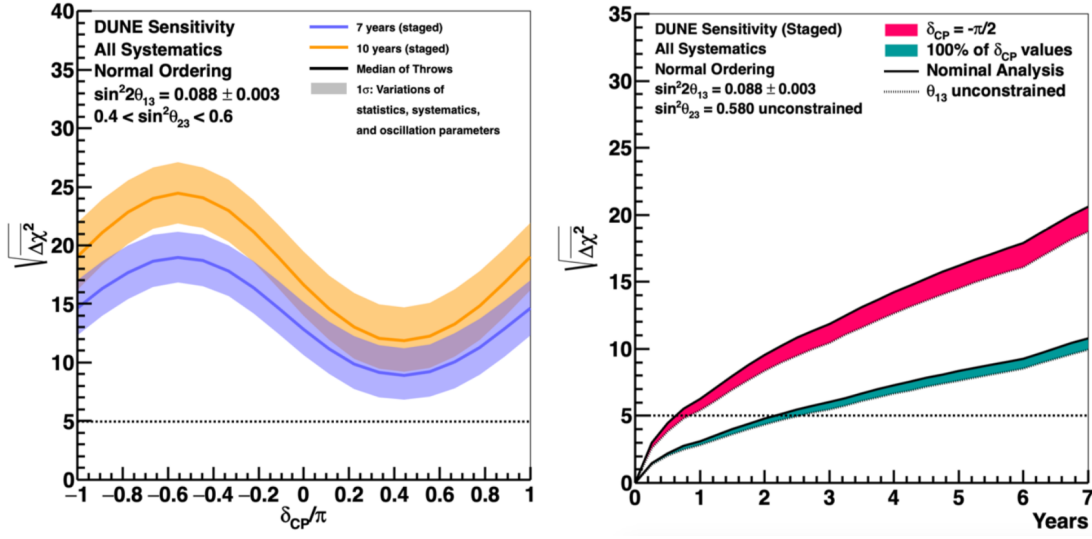


FIGURE 3.13: Significance of the determination of the neutrino mass ordering by DUNE [37]. Left panel: Significance as a function of the true value of δ_{CP} , for seven and ten years of data. Right panel: Significance for the case when $\delta_{CP} = -\pi/2$, and for 100% of possible true δ_{CP} values, as a function of time.

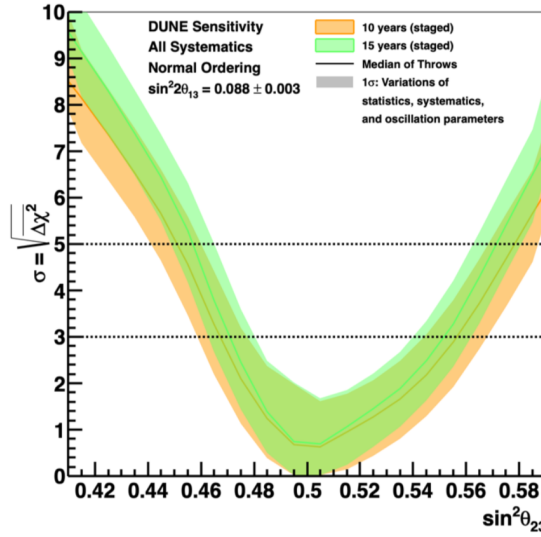


FIGURE 3.14: Sensitivity to determination of the θ_{23} octant by DUNE as a function of the true value of $\sin^2 \theta_{23}$, for ten and fifteen years of data [37].

octant will be determined. The sensitivity of DUNE to the octant is displayed in Figure 3.14 as a function of the true value of $\sin^2 \theta_{23}$.

3.4.2 Core-collapse supernova neutrino detection

DUNE is one of the next-generation supernova neutrino experiments [46, 110, 129] together with Hyper-Kamiokande [35] and JUNO [43] because of their size and neutrino interaction sensitivity, as already discussed in Section 1.6. The detection of the neutrino burst from a galactic core-collapse supernova is among the priorities of the DUNE science

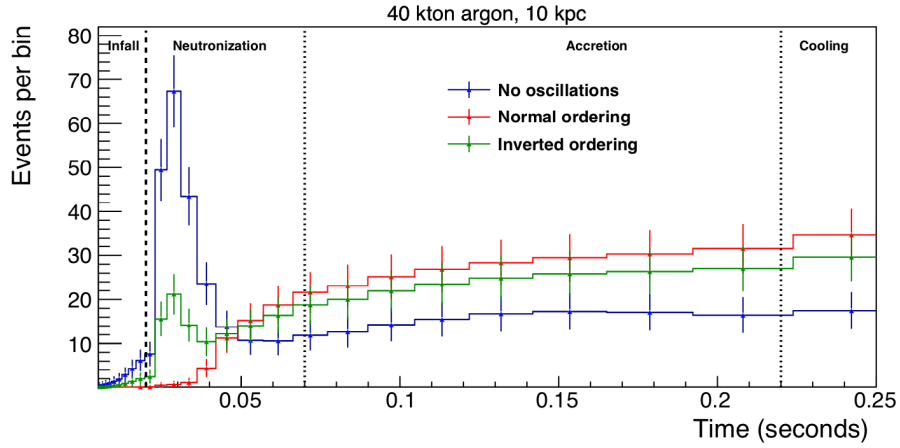


FIGURE 3.15: Expected supernova event rates versus time for the electron-capture model in [131] and 40 kt of argon: unrealistic case of no flavor transitions (blue), and including matter transitions for the normal (red) and inverted (green) mass orderings. Figure taken from [110].

program. DUNE sensitivity to the ν_e flavor will be extraordinary among past, current and future neutrino detectors, which are primarily sensitive to $\bar{\nu}_e$ via inverse beta decay.

The DUNE experiment will bring unique insight into both the neutrino properties and the core-collapse astrophysics towards a better understanding of the explosion mechanisms. The measurement of the supernova neutrino signal will be achievable thanks to the low energy threshold of the FD, which will be capable of detecting neutrinos from around 5 MeV to few tens of MeV.

In LAr detectors as DUNE, charge-current (CC) interactions of supernova neutrinos (~ 20 MeV) are detected as short electron tracks (up to a few tens of cm), often along with gamma-ray emission and secondary particle signatures. The triggering and reconstruction of such low-energy events involve particular challenges. The dominant supernova neutrino detection channel in LAr is the ν_e CC absorption [130]:

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* \quad (3.1)$$

In the process above, the observable is the ejected electron (plus the deexcitation products from ${}^{40}\text{K}^*$). Other channels of interest in LAr are the elastic scattering (ES) on electrons and the $\bar{\nu}_e$ CC interactions and the neutral-current (NC) scattering on Ar nuclei.

As explained in Section 1.6, the supernova neutrino signal contains wealth of information that can be directly associated to the supernova event. For example, the neutronization burst measurement (primarily composed of electron neutrinos) in DUNE will be a robust signature of mass ordering, as shown in Figure 3.15: for the normal ordering (NO) it is strongly suppressed, whereas for inverted ordering (IO) it is only partially suppressed.

DUNE will also have the ability to reconstruct the direction of the incoming neutrinos, which will help astronomers to promptly detect the supernova light. The pointing resolution

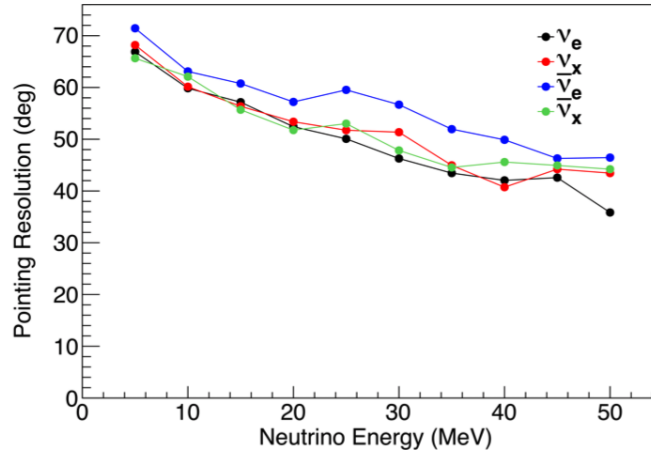


FIGURE 3.16: Pointing resolution of elastic scattering events detected in DUNE as a function of the neutrino energy for each neutrino flavor. Figure taken from [110].

of the reconstructed electron direction (angle at which 68% of angular differences are closer to truth) as a function of the true neutrino direction can be seen in Figure 3.16.

More details on the particular DUNE capabilities for supernova neutrino physics can be found in [110]. In particular, in this thesis, the light-based simulation studies on the supernova neutrino triggering efficiency with the proposed DUNE DP FD will be presented in Chapter 9.

ProtoDUNE Dual Phase detector

” *Be brave, be curious, be determined,
overcome the odds. It can be done.*

— Stephen Hawking

4.1 Introduction

As presented in the previous chapter, the ProtoDUNE Dual Phase (DP) detector [113, 124] is part of a rich R&D program currently underway at the CERN Neutrino Platform [122, 123] towards DUNE far detectors [34]. It aims at demonstrating the viability of the construction and operation of a tonne-scale liquid-argon time-projection-chamber (LAr TPC) with DP technology. A schematic of the detector is shown in Figure 4.1 and different views of ProtoDUNE-DP, including dimensions and positions of the elements, can be seen in Figure 4.2. Table 4.1 contains the specifications of some detector components.

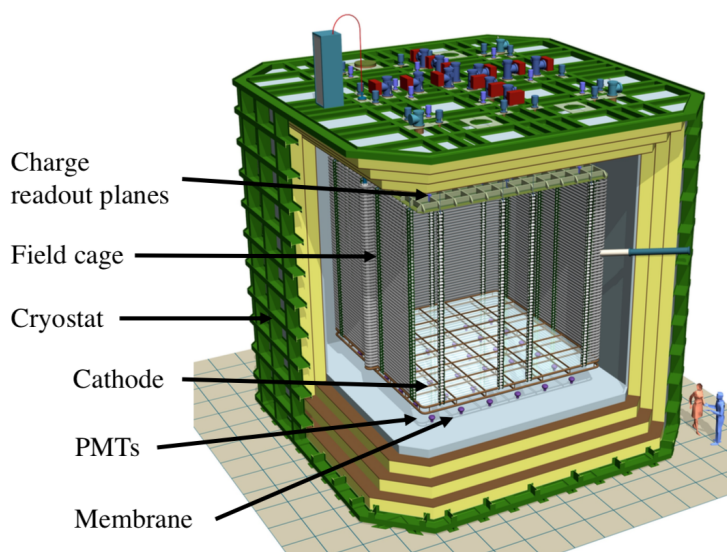


FIGURE 4.1: Schematic description of ProtoDUNE-DP. The main parts of the detector are indicated in the drawing.

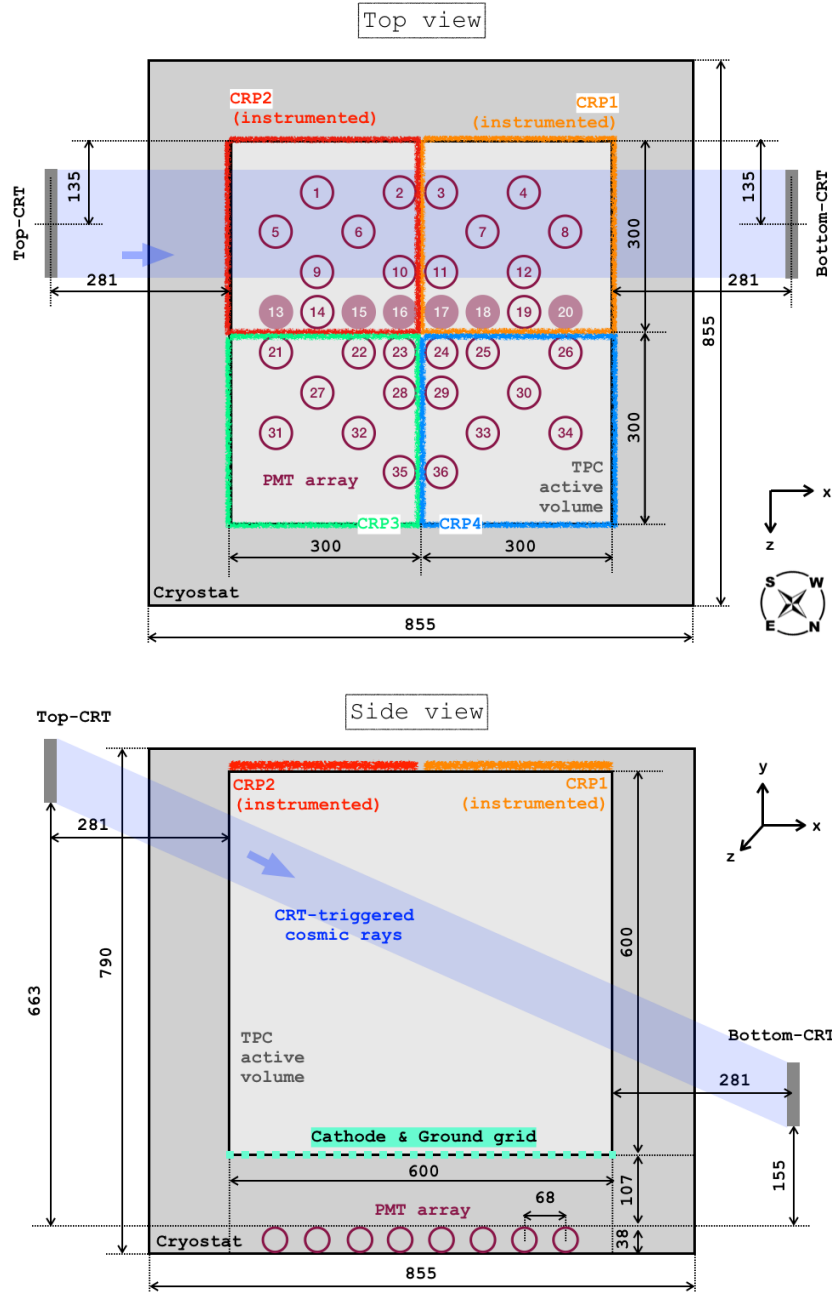


FIGURE 4.2: Views of the ProtoDUNE-DP detector. Dimensions and positions of the major elements are indicated (all in cm units). The charge readout planes (CRPs) labelled as 1 and 2 are instrumented, while the frames labelled as 3 and 4 are not. The photomultiplier tubes (PMTs) are represented with circles and, in the top view, the empty ones correspond to PEN PMTs and the filled circles to TPB PMTs. The two cosmic ray tagging (CRT) frames are displayed at the sides of the detector.

ProtoDUNE-DP is located in an extension to the EHN1 hall in CERN's North Area. The TPC has an active volume of $6 \times 6 \times 6 \text{ m}^3$, and contains a LAr fiducial mass of 300 t, being the largest DP LAr detector ever operated in the world. The drift is vertical along 6 m (half of the proposed total drift in DUNE) and the nominal drift field is 0.5 kV/cm. The

Component	Value	Unit
Cryostat outer dimensions	11.9×11.7×11.9	m ³
Cryostat inner dimensions	8.5×7.9×8.5	m ³
TPC active volume	6×6×6	m ³
Total LAr mass	750	t
Active LAr mass	300	t
LAr temperature	88	K
Nominal pressure at the cryostat	1045**	mbar
Maximum drift distance	6	m
Number of CRPs*	4	–
Number of fully instrumented CRPs	2	–
Surface per CRP	3×3	m ²
Number of channels per CRP	3840	–
Number of light readout channels	36	–
Number of CRT* panels	2	–
CRT panel active surface (H×V)	1.70 × 0.96	m ²
Nominal electric field	0.5	kV/cm
Nominal cathode HV	-300	kV

TABLE 4.1: Component specifications and conditions in ProtoDUNE-DP. *CRP: charge readout plane; CRT: cosmic ray tagging. **Since November 2019 (1010 mbar before).

charge readout is done in a plane at the top and the light detectors are located at the bottom of the cryostat. Hence, both systems are located at opposite ends of the detector and provide complementary measurements. Besides, the DP design enables to have a large homogeneous LAr volume without embedded passive materials, which allows a better event reconstruction. Thanks to its modular design, ProtoDUNE-DP hosts DUNE FD components in the 1:1 scale.

The basics of a DP LAr TPC technology and its advantages with respect to the SP approach were already discussed in Section 2.4. In this chapter, the different systems of ProtoDUNE-DP will be described (Sections 4.2-4.7), including a more extensive explanation on the features of the light detection system (Sections 4.8 and 4.9).

4.2 Cryostat and LAr purification system

The ProtoDUNE cryostat design [132, 133], common for SP and DP, is the result of a long optimization work by CERN engineers in collaboration with GTT/France¹. The so-called corrugate membrane technique (licensed by GTT) is based on a large experience in building large tanks to store and ship liquid natural gas (LNG) at cryogenic temperature. The special feature about this membrane is that it is capable to expand and shrink as a function of the temperature. This technology was already employed in the WA105 demonstrator [84]. The company responsible for the cryostat construction in both ProtoDUNEs was the

¹<https://gtt.fr>

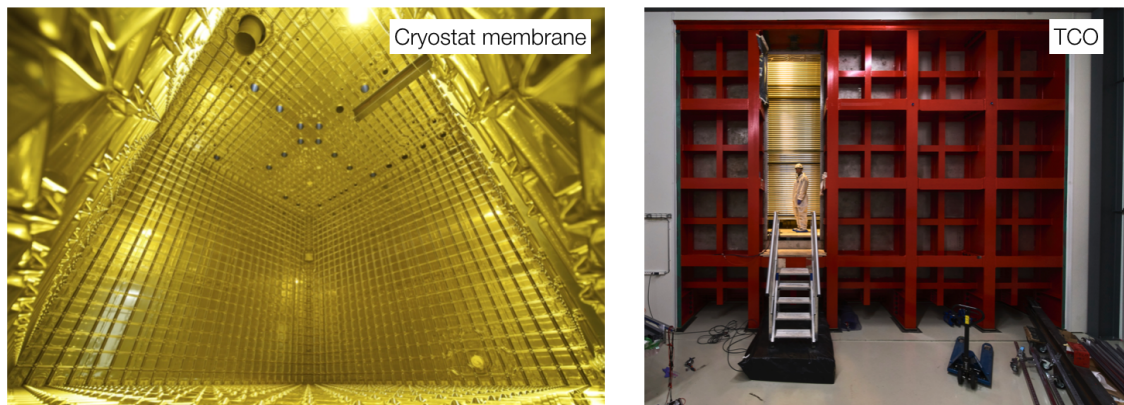


FIGURE 4.3: Left: Picture from the inside the cryostat membrane of ProtoDUNE-DP. Right: Picture of the TCO from the clean-room buffer.

Spanish firm Gabadi², authorized by GTT. A warm support structure houses the cold vessel which includes two layers: a primary corrugated stainless steel membrane and a secondary composite aluminum-glass fiber (triplex) membrane. A picture of the inner membrane is shown in Figure 4.3 left.

A clean-room buffer and a temporary construction opening (TCO) were placed on the left side of the cryostat (Figure 4.3 right) in order to insert the material through the TCO. Once the installation phase through the TCO was completed, this entrance was sealed and the access to the cryostat was only possible through the man-hole aperture on the cryostat roof.

A set of pipes penetrating the cryostat is used for the detector purging with gas argon (GAr) and for the LAr filling. The cryostat is equipped with a pumping system that continuously re-circulates the LAr, making it pass through a filtering system to remove the impurities (mainly water and oxygen). The purification filtering is also done when the LAr flows into the cryostat from the storage tank placed in the outside. The unclogging of the filters is required after some time of working, specially in the first stages of the purification process.

4.3 Very high voltage system

In ProtoDUNE-DP, the very high voltage system (VHV) system consists of [134]:

- **300-kV power supply:** from Heinzinger³, with a 10 m-long cable, delivering a maximum current of 500 μA .
- **VHV custom feedthrough:** from CINEL⁴, tested at the nominal voltage in a dedicated test stand before its installation. This element is required to bring the HV inside the cryostat.

²<http://gabadi.net>

³<https://www.heinzinger.com>

⁴<https://www.cinel.com/cinel>

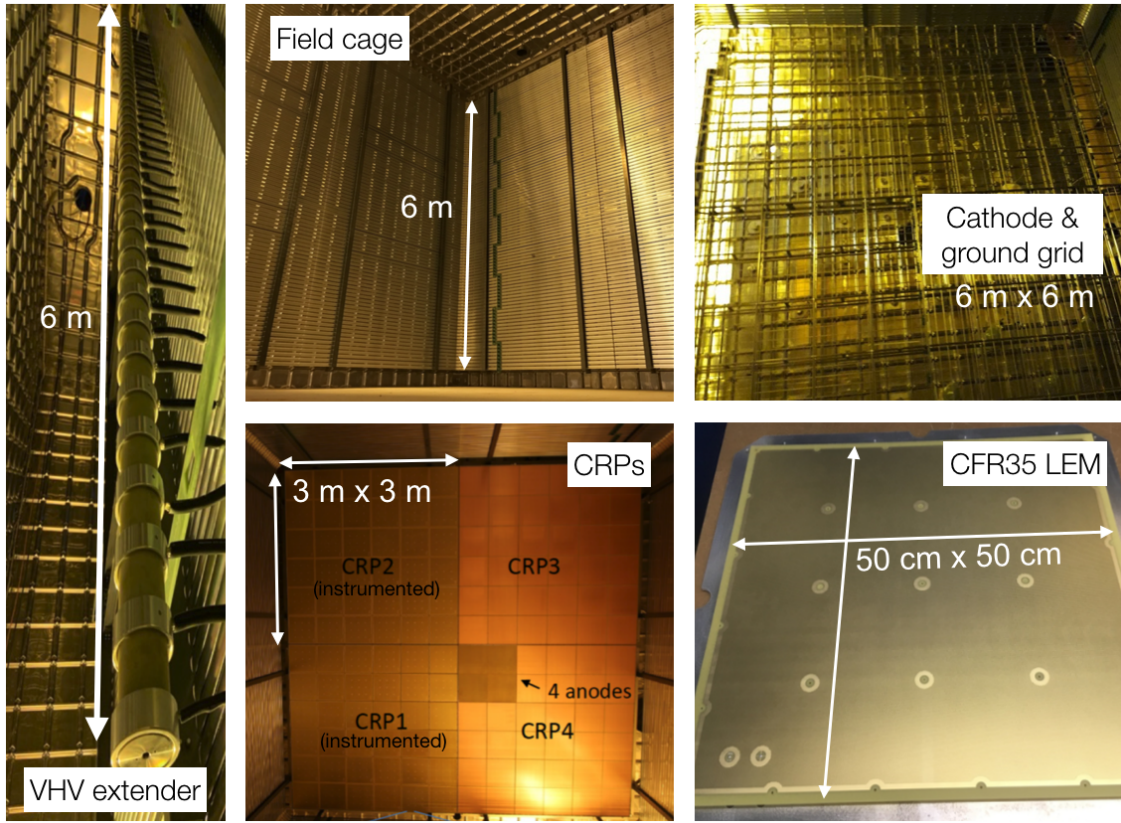


FIGURE 4.4: Pictures of some components of the VHV and the charge readout systems of ProtoDUNE-DP: VHV extender (left), field cage (top-center), CRPs (bottom-center), cathode and ground grid (top-right), and LEM unit (bottom-right).

- **HV extender:** it consists of a metal conductor enclosed in an insulator cylinder with a set of field shaping rings that mitigate the electric field in the vicinity of the HV connection. The HV extender is 6-m long and is needed to propagate the HV from the VHV feedthrough to the cathode (Figure 4.4 left).
- **Cathode and ground grid:** the cathode plane is a segmented structure (four $3 \times 3 \text{ m}^2$ modules) hanging $\sim 1 \text{ m}$ above the PMT array and suspended from the field cage (Figure 4.4 top-right). Since the PMTs are below, the cathode is made of stainless steel pipes of different sizes arranged in a grid so the light can go through the structure and reach the photon detectors. Moreover, the design minimizes the weight of the system. The ground-grid structure, just below the cathode, shields the PMT array from the cathode HV and is also composed of four $3 \times 3 \text{ m}^2$ modules interconnected.
- **Field cage, FC:** the role of this component is to ensure a uniform electric field along 6 m of drift. This is achieved thanks to equally-spaced field shaping electrodes (Figure 4.4 top-center). The target drift field inside the active LAr volume is 0.5 kV/cm and it is created by applying a HV up to -300 kV to the cathode. The FC is made of eight vertical modules of $6.3 \times 3 \text{ m}^2$ hung from the ceiling. Each module comprises 98 aluminium profiles, one on top of the other, held by fiber reinforced plastic frames.

The profiles are connected on the adjacent modules, forming 98 rings, one on top of the other, at specific voltages with a 6-cm pitch between neighboring rings. HV divider boards are used to apply the voltage at the rings. The equipotential rings have square shape with 6-m sides and a radius of curvature of 9 cm in the corners to mitigate regions with excessively high field (>30 kV/cm). The topmost resistor stage (first field shaper, FFS) is grounded to the membrane structure inside the cryostat.

4.4 Charge readout planes

The charge signal readout system in ProtoDUNE-DP consists of four charge readout plane (CRP) units at the top of the TPC. Two CRPs were fully instrumented with large electron multipliers (LEMs) [135] where charge amplification occurs while the other two were installed without (but with ground plates) due to time constraints (Figure 4.4 bottom-center). Thus, the instrumented charge readout surface covers 18 m^2 instead of the 36 m^2 initially envisioned. Each CRP is a 9-m^2 module and consists of the assembly of the extraction grid (submersed in liquid), the LEMs (placed in gas) and the anode (located in gas) in three-layered units called LEM-anode Sandwich (LAS). The mechanical structure integrating the LASs into the CRPs assures a large collecting area by minimizing the dead spaces. There are 36 $50\times 50\text{-cm}^2$ LASs per CRP.

An R&D program was carried out in order to improve the stability of the LEM design CFR-34 during operation [134]. As a result, the final LEM design (CFR-35) includes a larger clearance and copper guard rings in the peripheral parts of the LEM and around boundaries. The LEMs, produced by ELTOS⁵, are PCB epoxy plates of $50\times 50\text{-cm}^2$ (Figure 4.4 bottom-right) with a micro-pattern structure of $\varnothing 500\text{-}\mu\text{m}$ holes, drilled in a hexagonal pattern

⁵<http://www.eltos.com>

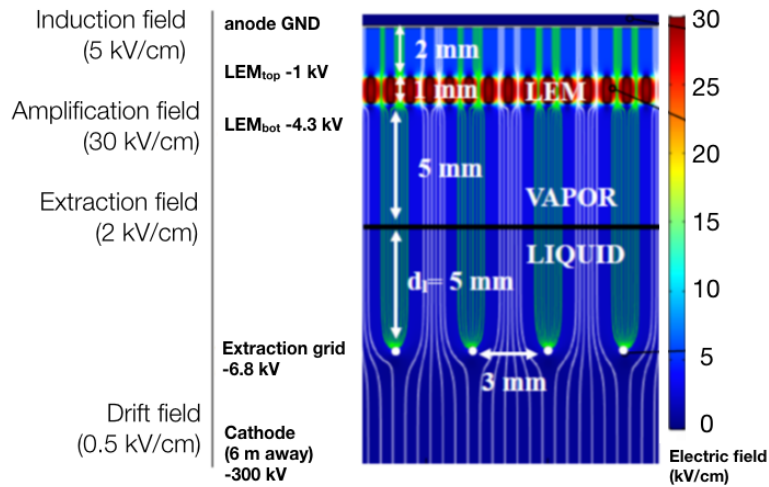


FIGURE 4.5: Nominal electric fields in the charge readout region. The simulated field lines indicate the electron paths.

(800- μm pitch). Concerning the anode, it was also produced by ELTOS and consists of two sets of 3.125-mm pitch gold-plated copper strips built with a 4-layer PCB, providing the two orthogonal views of the collected charge.

Figure 4.5 illustrates the nominal potential and field values applied in the CRP operation. The CRP assembly is positioned at the liquid-gas interface with precise inter-stage distances and inter-alignment for an efficient extraction, amplification and collection of the drifted electrons. A fine control of each CRP is performed by automated motors (three per CRP) with a precision better than 50 μm .

4.5 Charge readout electronics and DAQ

The data acquisition (DAQ) in ProtoDUNE-DP includes a global timing-trigger system that uses a White-Rabbit protocol⁶. The final charge readout (CRO) electronics [134] is the outcome of the R&D effort done since 2006 that aims at designing cost-effective electronics for large LAr TPCs. A subset of the CRO system (1280 channels) was commissioned in 2017 on the WA105 detector, proving an excellent operation during more than a year. The validation included the online storage and processing facility. In ProtoDUNE-DP, the raw data files are transferred to CERN (EOSPUBLIC⁷ and CASTOR⁸) and to Fermilab (data replication).

The front-end analog electronics, housed at the bottom of the chimney, is operated at cryogenic conditions while the digital electronics, located on the cryostat roof, works at room temperature. The cryogenic electronics are actively cooled to a temperature of about 110 K and is fully accessible without contaminating the cryostat inner volume. The CRO digital electronics and the DAQ system are based on 10 Gb/s Ethernet and use micro-telecommunications-computing-architecture (μTCA) cards in the advanced-mezzanine-card (AMC) format to read 64 channels per card. Regarding the data back-end system, it consists of an online storage-processing farm that operates at high data bandwidth (20 Gb/s).

A description of the light readout electronics will be given in Section 4.8.1. As it will be explained later, the light DAQ is independent of the charge DAQ although both systems can be synchronized thanks to the White Rabbit network.

4.6 Cryogenic instrumentation and slow controls

The stable conditions during the ProtoDUNE-DP operation are guaranteed by the cryogenic instrumentation and slow controls system (CISC), see Figure 4.6. It provides periodic information on the LAr quality and the monitoring of the detector operation [134]:

⁶<https://white-rabbit.web.cern.ch>

⁷<http://castor.web.cern.ch/castor>

⁸<http://information-technology.web.cern.ch/services/eos-service>

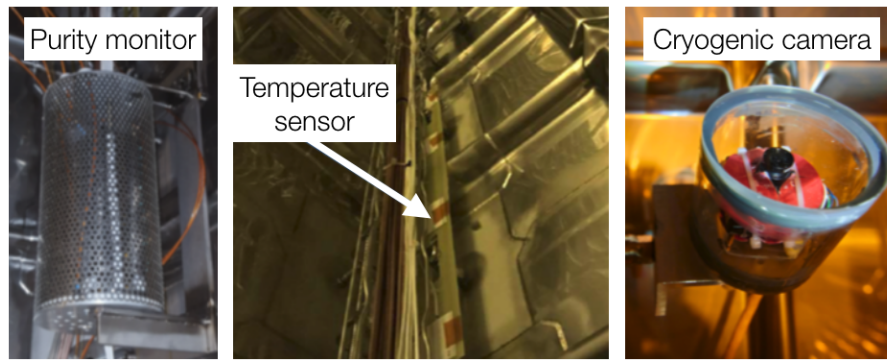


FIGURE 4.6: Pictures of some cryogenic devices of the CISC system: short purity monitor (left), temperature sensor (center), and cryogenic camera (right).

- **Temperature sensors:** installed along two vertical corners to obtain the LAr temperature profile along height (58 sensors); above CRPs to monitor the GAr temperature (24); on CRPs to estimate the deformations caused by thermal gradient (28); near LAr input pipes (6); at the insulation space (21); and underneath the cryostat (9). The most common sensor used is Pt1000 that enables a precision of 10 mK.
- **Level meters:** fundamental to control the LAr level with a precision better than 1 mm so the CRPs can be properly positioned and leveled. Capacitive devices were installed along one vertical corner to monitor the LAr filling and level stability (2 sensors); on the CRPs to control the CRP position with respect to the LAr surface (14); and on the cryostat walls to precisely measure the LAr level (2).
- **Purity monitors:** two short purity monitors (17-cm long) at one corner 2.5 m apart in height and one long purity monitor (48-cm long) on the cryostat floor, close to one of the short ones. These devices are crucial to control the LAr purity, determine when the filters need to be unclogged, and achieve a high performance of the detector.
- **Cryogenic cameras:** 1280×960 pixel Ethernet cameras sealed in transparent plexigla cylinders. In total, eleven cameras were installed: in the gas region pointing at the interface of two CRPs (4 cameras); in the gas to monitor the LAr level and the surface quality (1); looking at the LAr sprayers to watch the filling (1); and in the liquid (5) to see the cathode, the the bottom of the HV extender, the HV feedthrough, the PMT array and filling pipes, and a TPC corner from below. Together with the cameras, a LED lighting system was procured to ensure the successful imaging with the cameras.

The CISC system is key to take care of the detector conditions during the cryostat purging, cooling, LAr filling and re-circulation, and, eventually, the detector emptying.

4.7 Cosmic Ray Tagger system

The Cosmic Ray Tagger (CRT) trigger system of ProtoDUNE-DP consists of two panels located on the external cryostat walls with eight scintillator paddles (1.44 m × 0.12 m) per

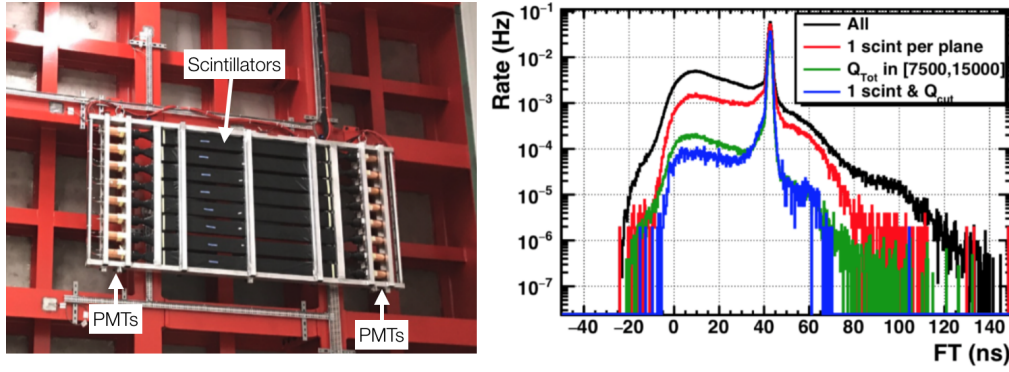


FIGURE 4.7: Left: Top CRT frame installed in ProtoDUNE-DP. Right: Event rate as a function of the ToF from TOP-CRT to BOT-CRT for different selection cuts (multiplicity per plane and total charge).

frame. The position of the CRT panels with respect to the cryostat appears in Figure 4.2: the top (bottom) CRT is at 6.63 m (1.55 m) above the PMT array. The active surface per CRT panel is approximately $1.70(\text{H}) \times 0.96(\text{V}) \text{ m}^2$. From the top view, it can be observed that the beam of cosmic rays defined by the CRTs crosses the LAr volume under the two instrumented CRPs, from southeast to northwest.

The CRT trigger system provides additional information on the cosmic muon track topology, allowing the 3D track reconstruction, independently of the reconstruction at the anode plane. This kind of external trigger scheme was also exploited in the WA105 demonstrator [85]. A picture of the top CRT frame on the cryostat wall can be seen in Figure 4.7 left. The DAQ of the system is continuously running with an acquisition frequency of 0.3 Hz, and runs are automatically started and stopped every 24 h. The rate is relatively low because cosmic muon flux reaching the Earth’s surface is mostly vertical [1] and the CRTs select diagonal tracks.

Each scintillator paddle includes PMTs placed at both ends for the charge readout using custom compact μTCA boards (eight channels per board). The trigger logic is based on the analog sum of the two PMT signals per paddle. A coincidence between the two CRTs is required for a trigger. The signal detected by each panel is timestamped by an internal clock (1-s precision) and allows a later off-line matching between the CRT and PDS events. The time-of-flight (ToF) from the top (TOP-CRT) to the bottom (BOT-CRT) panel is evaluated and a *clean* coincidence occurs when both CRTs trigger with a time difference between 40 and 45 ns (see Figure 4.7 right). The rate of clean coincidences is found to be 0.11 Hz.

4.8 Photon detection system

In a LAr TPC detector, the photon detection system (PDS) provides the trigger for non-beam events, allows the precise determination of the absolute event time for a full 3D reconstruction, and enables calorimetric measurements [113]. The scintillation light can

be also exploited for cosmic background rejection and particle identification. A summary of the varied purposes of the light detection in a LAr TPC was already presented in Section 2.6.

An overview of the design of the ProtoDUNE-DP PDS, based on PMTs, is presented in this section. CIEMAT and IFAE (Institut de Física d'Altes Energies, in Spain) were in charge of the design, procurement, validation, installation and operation of both the PDS and the calibration system (see Section 4.9). Note that the information on the PDS given in this chapter is more extensive than the descriptions of other detector systems as the scintillation light detection is the central topic of this thesis.

4.8.1 PDS design

The design of the PDS embedded within ProtoDUNE-DP [118, 136, 137] calls for 36 cryogenic PMTs placed on the membrane floor, underneath the cathode grid and within the membrane corrugations. The PMT layout in the detector is shown in Figure 4.8. In the diagram, two groups of PMTs are distinguished depending on the wavelength shifter (WLS) material employed (see Section 4.8.4): there are 6 PMTs with TPB coating evaporated on their surface placed along a central line (full circles), and 30 PMTs that include a PEN sheet above the photocathode (empty circles).

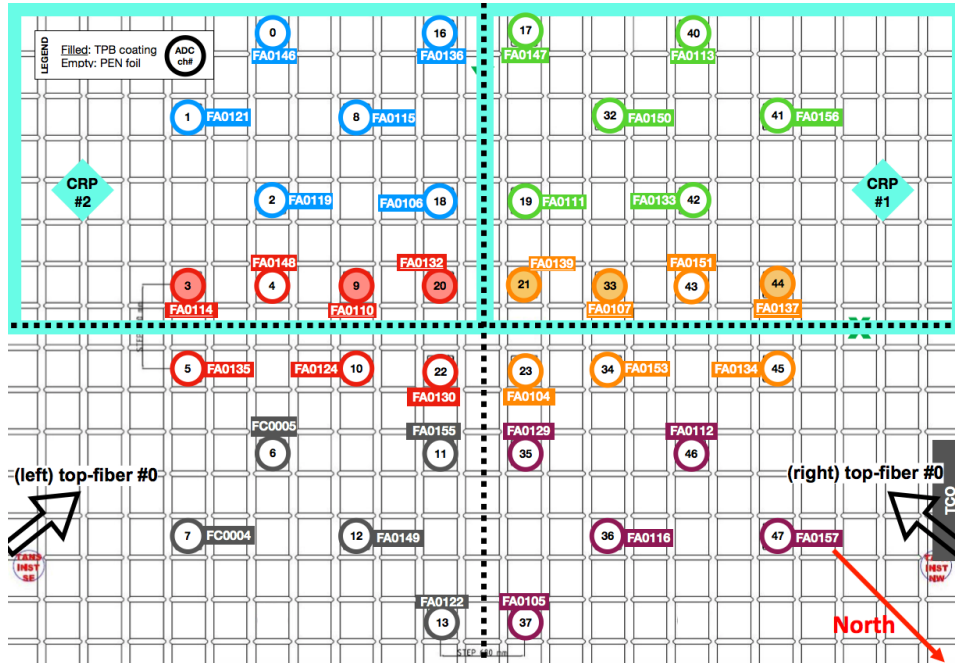


FIGURE 4.8: Top view of the ProtoDUNE-DP PMT layout: the ADC channel number, serial number (FA0XXX or FC000X) and wavelength shifter of the PMT are indicated. The PMTs illuminated by the same LED for calibration are identified with the same color and the positions of the top-fibers are pointed out. The region covered by the two instrumented CRPs is inside blue squares and the TCO position is indicated.

The non-uniform PMT distribution over the 36 m² active area was optimized with simulation studies to achieve a better coverage of the light produced by cosmic muons [138]. However, a modification of the baseline layout was done during the installation phase: two PEN PMTs (namely, FA0148 and FA0151) were moved from a border to the center in order to complete the central line of PMTs; each one was installed between two TPB PMTs in order to fill the gaps along that line. The main motivation for this change was to have more PMTs near the TPB ones to support the foreseen PEN-TPB studies.

4.8.2 PMT unit

The PMT model selected for the PDS is the R5912-20Mod from Hamamatsu⁹. The parts of the PMT unit can be seen in the picture of Figure 4.9. Some features of this PMT model are [139]:

- The photocathode has a diameter of 8 inch (202 mm): a PMT model with a large photocathode surface was selected given the extensive active area in the detector that must be covered (~ 36 m²).
- The PMT has a 14-stage dynode chain and a nominal gain of 10^9 (~ 1500 V) at room temperature (RT). Thus, the gain loss due to the operation at cryogenic temperature (CT) is compensated and the required voltage is lower. In particular, the dynode structure is Box & Line: the first dynode has a large area and the electron paths are progressively focused through the chain (linear-focused configuration).
- The spectral response of the PMT is between 300 nm and 650 nm, with a peak wavelength of 420 nm. The quantum efficiency (QE), defined as the fraction of incident photons at the photocathode converted into photo-electrons, is a property that depends on the light wavelength. The expected QE of this particular PMT

⁹<http://www.hamamatsu.com>

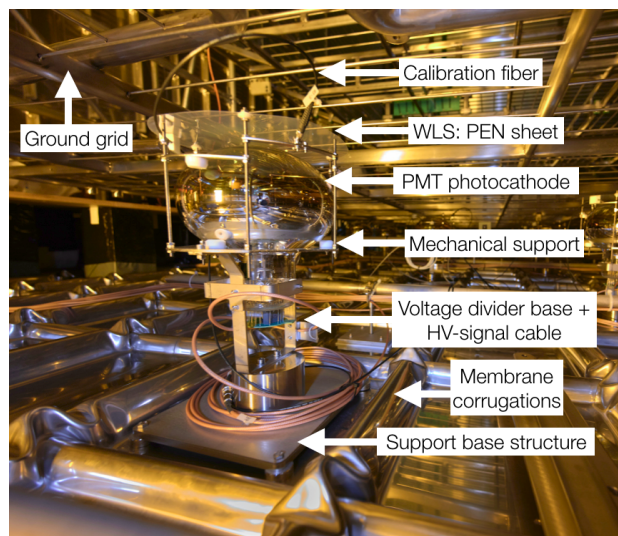


FIGURE 4.9: Picture of a PMT with PEN sheet in ProtoDUNE-DP. The main parts are indicated.

(around 20%) will be discussed in Section 4.8.4. In order to preserve the QE at cryogenic temperature, a thin platinum layer was installed between the bi-alkali photocathode and the borosilicate glass envelope of each PMT.

The exact PMT model was already successfully operated in the WA105 demonstrator [85] and similar PMTs were employed in other LAr experiments such as MicroBooNE [119], ICARUS T600 [120], MiniCLEAN [140] and ArDM [141]. Hence, a good performance at CT is expected.

A mechanical support of 304L stainless steel ensures the stability of the PMT unit on the membrane. The materials of the support were selected to minimize the mass, and the shrinking during the cooling process was taken into account. The buoyancy forces in the LAr are overwhelmed thanks to the weight of the PMT itself (~ 1.1 kg) and of the stainless steel support base structure. Besides, the large surface of the support base counters the possible lateral forces due to the liquid flow. A flotation test with one PMT immersed in LAr was carried out to verify this behaviour in the liquid.

4.8.3 Positive bias base

A positive bias voltage-divider base design is chosen in ProtoDUNE-DP (Figure 4.10): positive high voltage (HV) is applied at the PMT anode while the photocathode is grounded. The so-called positive base (PB) configuration is preferred because, according to its use in the WA105 demonstrator [85], it reduces the noise, expands the PMT linearity range, and needs only one coaxial cable to carry the HV and receive the PMT signal, minimizing the number of required feedthroughs.

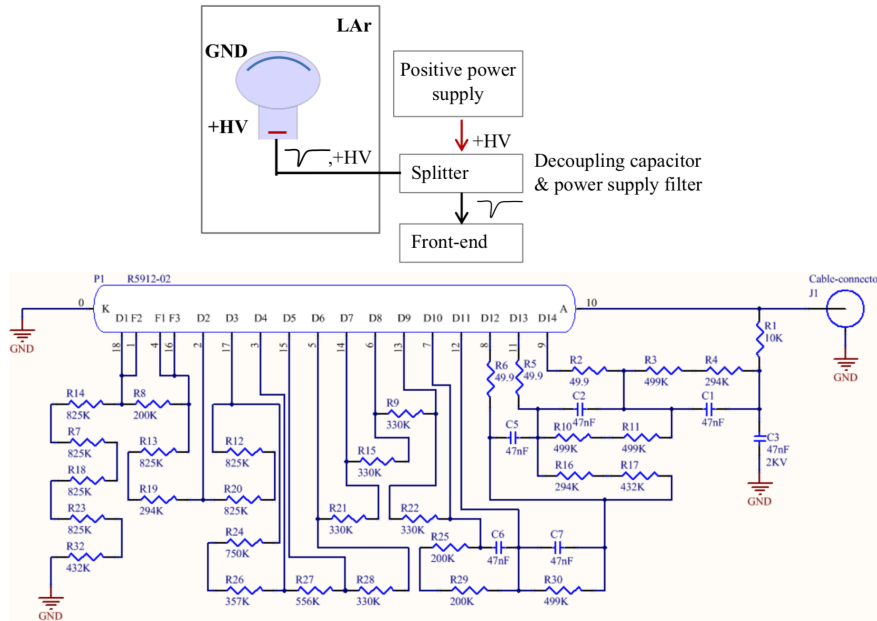


FIGURE 4.10: Schematic (top) and dynode diagram (bottom) of the PMT positive base.

With the PB configuration, a dedicated decoupling circuit is necessary to split the HV and the PMT signal outside the cryostat. The PB, designed with passive components due to the degraded performance of semiconductors at CT, has $13.4\text{ M}\Omega$ of total resistance, an average current of $100\text{ }\mu\text{A}$ and a dissipated power of 0.14 W .

4.8.4 Wavelength shifting methods

PMTs are sensitive to light of wavelength from 300 to 650 nm (visible range). According to the measurements performed by the manufacturer on 3 PMTs of ProtoDUNE-DP, the QE at RT is maximal around 390-410 nm and almost null for wavelengths below 200 nm (see an example in Figure 4.11 left). Hamamatsu measured an average QE value of 0.183 ± 0.013 at 430 nm. Therefore, in order to efficiently detect the LAr scintillation light emitted at 127 nm [76], a WLS material is required to convert the VUV photons into visible light.

The ProtoDUNE-DP PDS relies on two different WLS methods (see Figure 4.12): 6 PMTs are directly coated with tetraphenyl butadiene (TPB) and 30 PMTs are covered with polyethylene naphthalate (PEN) foils. Both TPB and PEN have a maximum of re-emitted photons around 430 nm [142]. On the one hand, TPB is an organic fluorescent chemical compound, extensively employed in particle physics experiments [143, 144]. The main drawbacks to this conventional WLS method are the hardly-scalable coating procedure to large surfaces (for next generation kt-detectors like DUNE), and that the aging and long-term performance are not completely well known. On the other hand, PEN [145] is a thermoplastic with fluorescent properties that have been largely studied but whose efficiency as WLS in a LAr detector had never been investigated before. In fact, the first measurement on the PEN efficiency in such conditions (and relative to the TPB performance) has been done in ProtoDUNE-DP [146].

In the WA105 demonstrator, it was proven that the direct TPB evaporation on the photocathode is a better option than depositing the TPB on an acrylic plate on top of the PMT, in terms of the light collection [85, 86]. Initially, the 40 previously-characterized PMTs (36 to be installed plus four spares) were coated with a thin TPB layer directly deposited on the PMT polished window. The coating density was 0.2 mg/cm^2 , corresponding to a thickness of about $0.2\text{ }\mu\text{m}$. More details on the coating procedure will be given in Section 6.2.1. After the TPB coating, four PMTs were sent to the INFN-Pavia laboratory for a QE measurement at RT. The relative QE uniformity along the photocathode diameter (Figure 4.11 top-right) and the absolute QE as a function of the light wavelength (Figure 4.11 bottom-right) were investigated. All the tested PMTs showed a very uniform QE with respect to the center (top of the photocathode), and the average QE at 127 nm obtained was 0.14 ± 0.02 . The QE was measured by comparing the current given by the PMT under test and by a reference calibrated photodiode in a dedicated setup. The average result is compatible with the QE value given in [147] for the PMTs of ICARUS using the same setup: 0.12 ± 0.01 .

Although an stable performance of the TPB coating is expected when the PMTs are immersed in LAr, the LAr drops sprayed from nozzles inside the cryostat (to achieve a

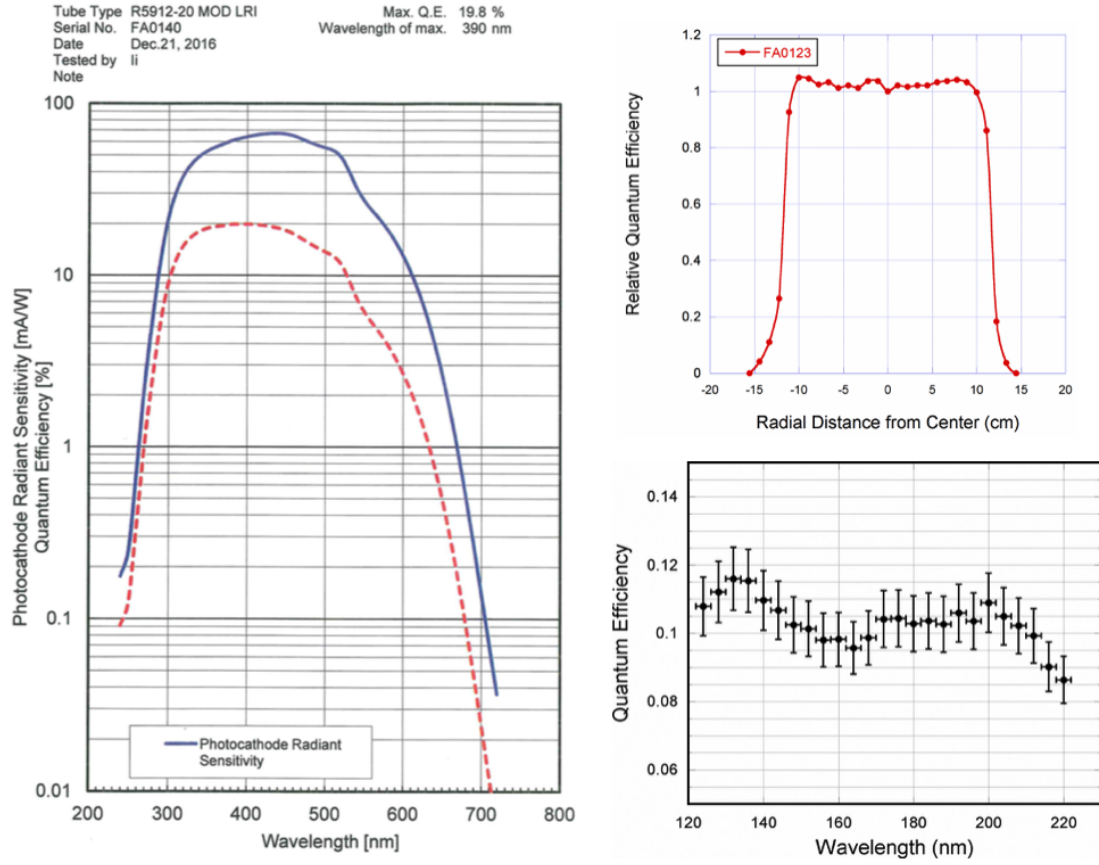


FIGURE 4.11: Left: QE (dashed red line) and radiant sensitivity (solid blue line) vs. light wavelength for one PMT measured by Hamamatsu before the TPB coating. Top-right: Relative QE along the photocathode diameter measured at the INFN-Pavia laboratory after the TPB coating. Bottom-right: example of QE vs. light wavelength measured at the INFN-Pavia laboratory group after the TPB coating.

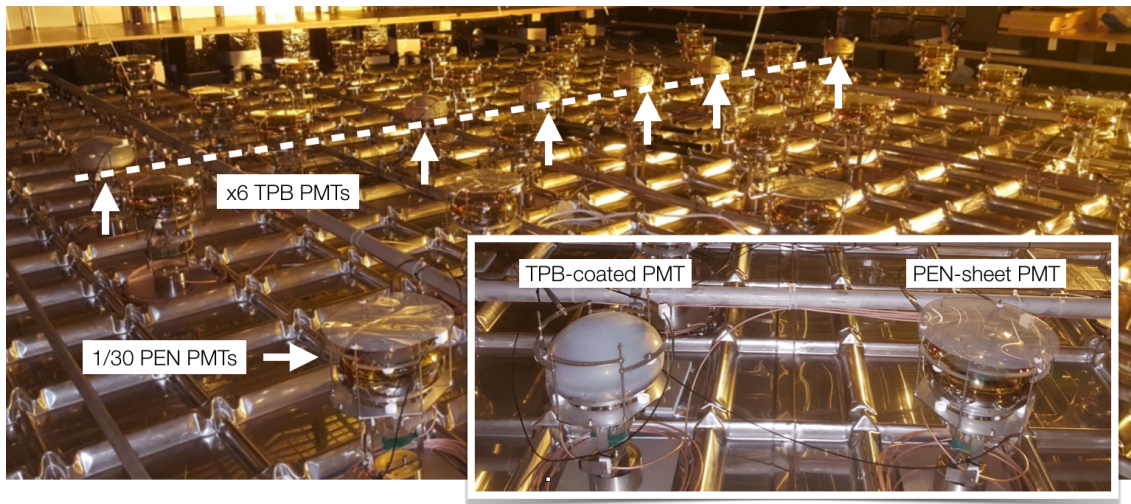


FIGURE 4.12: PMT array where the 6 TPB-coated PMTs placed along a central line can be observed, as well as the PEN sheets on the other PMTs. On the bottom-right corner, a closer picture of one TPB PMT and one PEN PMT is shown.

uniform initial cooling of the detector) could reach the PMTs and damage the TPB coating. In that case, some TPB dust could float up to the liquid-gas interface, what would be fatal for the TPC operation. Such a risk is avoided by using PEN as WLS. This and other advantages of PEN with respect to TPB (like the easier installation of the foils compared to the coating process) motivate the investigation of the PEN performance in a prototype as ProtoDUNE-DP. Therefore, a circular sheet of PEN (24-cm diameter, 0.125-mm thickness) was placed tangent to the PMT glass surface in 30 PMTs and the 6 PMTs left were installed with the original TPB coating. The PEN sample employed was transparent and biaxially oriented, manufactured by GoodFellow¹⁰.

4.8.5 Light readout electronics and DAQ

A custom light DAQ software [148] provides a user-friendly configuration of the data-taking parameters. It controls the following systems:

- **PMT power supply:** PMTs are biased using three CAEN¹¹ A7030 modules with 12 channels each. The typical operating HVs are between 1100 V ($\sim 1 \cdot 10^7$ gain) and 1800 V ($\sim 5 \cdot 10^7$ gain).
- **Calibration light source:** a black box with 6 LEDs and a SiPM (see next section) is controlled by a BeagleBone Black¹² board, an open-hardware mini computer running a Debian Linux distribution. Some of the configurable calibration options are the LED bias voltages and frequencies, the SiPM voltage, and the HV step and waiting time between consecutive runs.
- **Light DAQ:** based on the commercial ADC V1740 from CAEN with 64 analog input channels (12 bits, 2 Vpp dynamic range, and maximum sampling rate of 62.5 MHz). It allows to program a trigger logic based on the desired number of PMTs detecting in coincidence over a given threshold level. The ADC is connected to the LRO computer by a 80 MB/s optical link (CAEN CONET2). The light DAQ is based on MIDAS, a framework developed by PSI and TRIUMF¹³, which was already successfully employed in the WA105 demonstrator [84]. A White Rabbit SPEC card is installed on the LRO computer to generate a timestamp on reception of the global trigger signal.

As the data collected by the CRO system, the light data (both the original MIDAS files and the converted ROOT¹⁴ files for data analysis) are also transferred every day to EOSPUBLIC¹⁵ and CASTOR¹⁶.

¹⁰<http://www.goodfellow.com/E/Polyethylene-naphthalate-Film.html>

¹¹<http://www.caen.it>

¹²<https://beagleboard.org>

¹³<http://midas.triumf.ca>

¹⁴<https://root.cern>

¹⁵<http://castor.web.cern.ch/castor>

¹⁶<http://information-technology.web.cern.ch/services/eos-service>

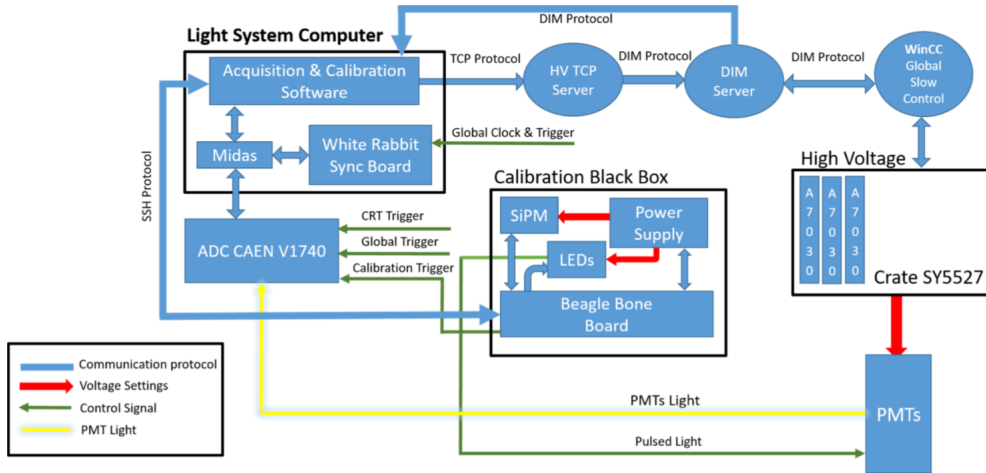


FIGURE 4.13: Diagram of the LRO system of ProtoDUNE-DP [148].

The light readout (LRO) system collects and digitizes the signals from the PDS. A schematic of the system can be seen in Figure 4.13. The front-end starts the acquisition once an input signal is received from the trigger source. The possible trigger modes of the PDS are the following:

- **Calibration trigger** (typical frequency: ~ 1 kHz): an external trigger signal (NIM) synchronized with an LED pulse is sent from the calibration light source. This option can be also used as a **random trigger** with configurable frequency by inhibiting the LED light.
- **PMT self-trigger** (Hz-kHz): in this mode, the trigger is based on the detection by selected PMTs above a certain threshold during a time window. The LRO front-end provides a trigger signal (NIM) to the DAQ global trigger computer (GTC).
- **Global DAQ trigger** (~ 10 Hz): it provides a common trigger for both the charge and light detection systems. The White Rabbit system assigns timestamps to the events with a 1-ns precision, allowing the later unambiguous matching of each light event with its charge peer.
- **CRT trigger** (~ 0.3 Hz): the CRTs provide the trigger signal for cosmic muons crossing both panels.

Data taken with all the trigger modes above except the global DAQ trigger are analyzed to obtain the results contained in this thesis.

4.9 Light calibration system

The light calibration system (LCS) [149, 151] is key to ensure a high performance of the PDS. The main goal of the LCS is the control of the PMT gain in situ, during the operation of the detector. Thus, it allows to set a common threshold definition for all the PMTs thanks to an equalized PMT response, simplifying the determination of the triggering efficiency.

In particular, the PMT calibration is fundamental to achieve an uniform light detection among the PMTs, which allows the combination of measurements from different PMTs to obtain the final results presented in this thesis.

The design of the ProtoDUNE-DP LCS is reviewed in this section. The LCS illuminates the PMT photocathode at the single photo-electron (SPE) level in order to determine the gain, albeit the system can also provide light at higher levels to study the PMT response linearity. The target measurements of the LCS are: 1) the gain at the operating voltage; 2) the gain calibration curve doing a HV sweep; and 3) the PMT response at several photo-electrons (PE) level for linearity studies.

4.9.1 Baseline LCS design

The LCS design is shown in Figure 4.14 and some details on the components can be found in Table 4.2. The light source is operated from out of the cryostat and provides a configurable amount of light. The calibration light rate is kept within $\sim$ kHz to avoid the PMT fatigue (see Section 5.2.2.3). The light source consists of six blue LEDs placed in a hexagonal geometry, and a SiPM as reference sensor at the center to detect the stray light and check the LED performance. The LEDs use a Kapustinsky [150] circuit as driver.

The emitted calibration light is transmitted through a fiber system. Each LED is connected to an external fiber going to one optical feedthrough in the instrumentation flanges on the top of the detector. Inside the cryostat, six fibers transmit the light to six 1-to-7 fiber bundles that are attached (one bundle per fiber). Then, each fiber bundle end points at one PMT photocathode and is fixed to the PMT support structure using a SMA

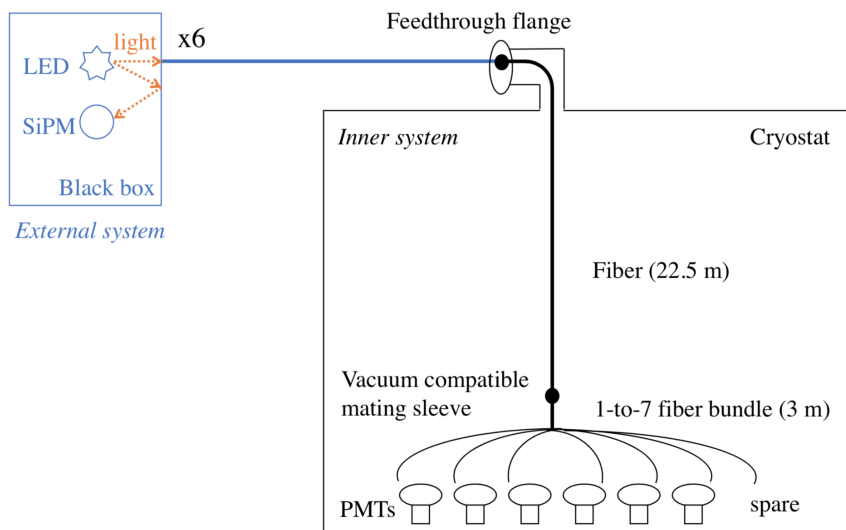


FIGURE 4.14: Final configuration of the ProtoDUNE-DP LCS [151]. The components placed inside the cryostat at CT are represented in black and the external ones at RT in blue.

Qty.	Component	Manufacturer	Reference	$\varnothing$ (μm)	L (m)
1	Black box	Thorlabs	XE25C9D/M	–	–
6	LED (465 nm)	Nichia Corp	NSPB300B	–	–
1	SiPM	SensL	MicroFJ-30035-TSV-TA	–	–
6	External fiber ¹	Thorlabs	FG105LCA-CUSTOM-MUC	105	9.5
2	Feedthrough flange	Allectra	152-FCF-C40-3	3200	–
6	Inner fiber ²	Thorlabs	FT800UMT	800	22.5
6	Mating sleeve	Thorlabs	ADASMAV	3.2	–
6	1-to-7 fiber bundle ³	Thorlabs	FT200UMT	200	3

TABLE 4.2: LCS components [151]. All fibers are 0.39 NA (numerical aperture) TECS™ hard clad, multimode, step-index fibers with SMA connectors. ¹ Low OH. ² SS jacket, high OH. ³ SMA, SS jacket at the common end (25 cm), black jacket at split ends, high OH, $\varnothing 200 \mu\text{m}$ each fiber.

connector. Since only 36 fibers are needed, one fiber per bundle is not connected and is kept as spare fiber.

The components placed outside the cryostat are considered the *external system* whereas the *inner system* is formed of the components installed inside the cryostat. The external and internal systems operate at RT and CT, respectively. Further description of both systems is given below. Their designs are driven by the goal of having a cost-effective prototype system scalable to future detectors as the proposed DUNE DP FD.

4.9.1.1 External system

The external system was developed at IFAE. The LED has a peak wavelength of 465 nm (matching the wavelength for maximum PMT QE) and allows the coverage of a wide range of light levels to carry out different studies. A custom light guide structure with six arms (Figure 4.15 left) was produced using a 3D printer and installed in a commercial black box from Thorlabs. It allows to distribute the light among the different components. A SiPM that serves as reference sensor is assembled in the central part of the structure and is key to monitor the LED stability (Figure 4.15 right). A PCB with the Kapustinsky circuit is mounted on each arm for the injection of the light in form of several-ns long pulses. The baseline circuit includes a low-pass filter to minimize the effect of the electrical pulses on the electronics control. Each LED is placed on the PCB in front of a SMA feedthrough with a 9.5-m optical fiber connected. The light is transmitted through the fibers to the instrumentation flanges at the cryostat roof. There are three female optical feedthroughs per flange.

The stray light is a small fraction of the light emitted by the LEDs and is detected by the SiPM. This reference sensor is operated at a voltage around 30 V and provides two signal outputs: a fast signal of a few-ns width and a slow signal of a few-ns rise time and a long tail of some hundreds of ns. The slow output signal can be used by an external digitizer. The SiPM is mounted on a PCB that is connected to a BeagleBone Black module using a

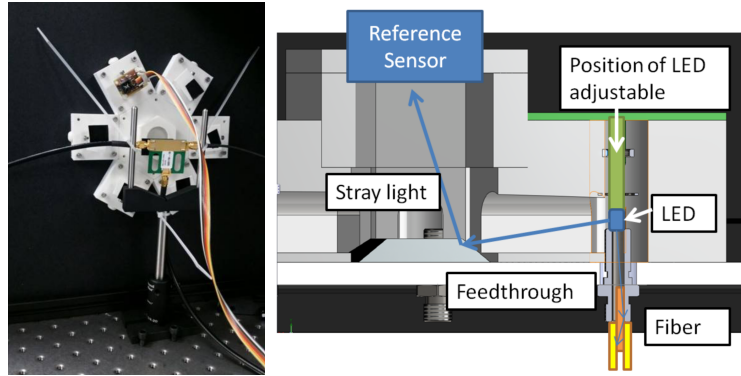


FIGURE 4.15: Left: Picture of the light guide structure during the development phase. Right: Schematic path of the light from the LED to the reference sensor.

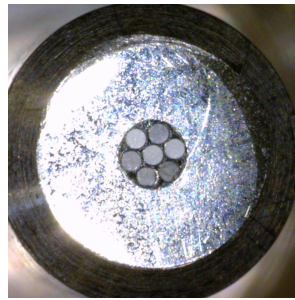


FIGURE 4.16: Common end of a 1-to-7 fiber bundle.

DB25 connector. This module is placed outside the black box and contains the control software and firmware. It has a built-in 12-bit ADC that digitizes and calculates the integral of the pulse. The operation parameters of the BeagleBone are controlled via Ethernet connection and the signals are collected by a custom shield board that concentrates them in a DB25 connector.

4.9.1.2 Inner system

The inner fiber system, developed at CIEMAT, is designed to maximize the light transmission from the flange to the PMTs, in cryogenic conditions. Various tests were performed to characterize some of the potential LCS components and select the optimal configuration in terms of light transmission and mechanical safety. There is a 22.5 m-long fiber going down from each optical feedthrough. These fibers are routed along the walls of the cryostat to the bottom where a 1-to-7 fiber bundle (Figure 4.16) is connected to each fiber. In total, 36 fibers are guided to the PMTs (one per PMT) with their ends fixed to the PMT support structure using a SMA connector so the fiber points at the photocathode.

The inner fibers are chosen to have high OH (hydroxyl) ion concentration to increase the transmission at the wavelength of the light source. The fiber diameter ($800\text{ }\mu\text{m}$) is selected for an optimal light transmission in the fiber-bundle coupling: the section is large enough at the bundle entrance (diameter of $700\text{ }\mu\text{m}$ in total) given the NA (numerical

aperture). A vacuum compatible SMA to SMA mating sleeve is used in the fiber-bundle connection to ensure a good light homogeneity.

The PMT orientation in the detector and the position of the fiber with respect to the PMT photocathode were carefully chosen for an optimal calibration. The first dynode is perpendicular to the Earth magnetic field and the fiber is parallel to the first dynode to avoid that the magnetic field moves the photo-electron away from the first dynode reducing the PMT gain.

4.9.2 Alternative LCS design

An alternative LCS was installed in ProtoDUNE-DP with the purpose of reducing the total number of fibers and feedthroughs (and, thus, the cost) in future larger detectors. The alternative configuration consists of two fibers at the top of the field cage pointing to the center of the detector, so one fiber can illuminate several PMTs. Each fiber is a 5-m long fiber from Thorlabs (FT800UMT, $\varnothing 800 \mu\text{m}$, multimode, high OH) with a SMA connector at the end connected to the external LCS. By default, the baseline system is arranged in the detector. In order to take measurements with the alternative LCS, one of the external fibers (one LED) should be connected to the alternative inner fiber in the corresponding flange. A diagram of the alternative LCS and a picture of one of the top-fibers can be seen in Figure 4.17. The position of the top-fibers in the detector was already displayed in Figure 4.8.

As the calibration light in the alternative LCS must go through more than 6 m of LAr from the fiber end to the PMT array, the setup to characterize the performance of such a configuration is not simple and, hence, the alternative system is tested directly in ProtoDUNE-DP. However, further optimization of the alternative option, as the one carried out for the baseline one in the laboratory (presented in next chapter), would be needed after ProtoDUNE-DP operation for a complete validation.

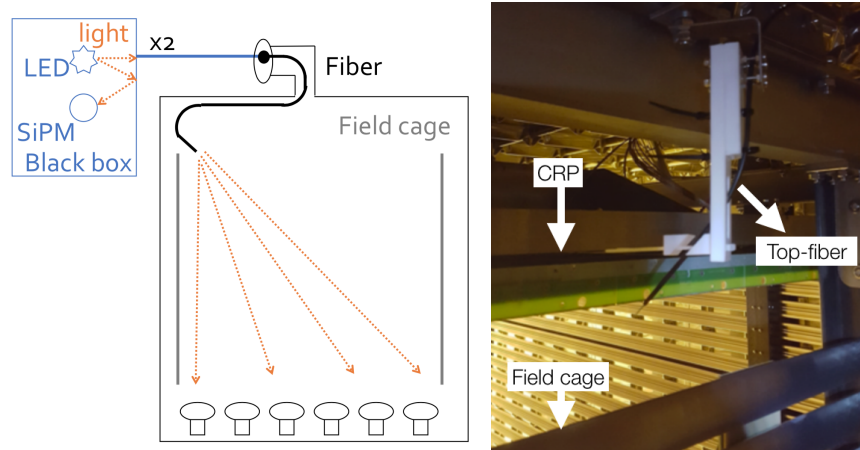


FIGURE 4.17: Schematic (left) and picture (right) of the alternative LCS.

Validation of the ProtoDUNE-DP PDS and LCS before installation

” *All the world is a laboratory
to the inquiring mind.*

— Martin H. Fischer

5.1 Introduction

The successful operation of ProtoDUNE-DP, a complex 300-t DP LAr TPC described in the previous chapter, relies on the excellent performance of the different detector systems. As ProtoDUNE-DP is based on the novel DP technology and includes components from recent R&D activities, the individual validation of the elements prior to their installation in the detector becomes essential. In this chapter, the measurements of the PDS and LCS component response before the installation in ProtoDUNE-DP are reviewed. Tests on the basic component performance are carried out as well as additional measurements on the PMT unit behaviour to obtain other valuable results.

The characterization of all the PMT units prior to the installation is summarized in Section 5.2 and the additional measurements of the PMT cryogenic operation (response linearity) are detailed in Section 5.3. Section 5.4 presents the results of some PMT tests in over-pressure conditions as the ones expected at the bottom of a 10-kt DUNE FD module. Finally, the characterization of the individual components of the LCS and the validation of the full calibration chain are reported in Section 5.5.

It is worth pointing out the interest of the studies presented in this chapter for other LAr-based detectors where the scintillation light is detected by PMTs. Thus, the results that will be reviewed in the next sections are also contained in three publications on: the PMT characterization and further validation [118], the PMT tests with over-pressure [152], and the LCS validation [151]. The research on the two last topics has led to the publication of technical notes as well [149, 153].

5.2 PMT characterization

The characterization of 40 (36 + 4 spares) Hamamatsu R5912-20Mod cryogenic PMTs for ProtoDUNE-DP (see the PMT unit description in Section 4.8.2) was carried out in 2017-2018 at CIEMAT, both at room (RT) and cryogenic (CT) temperatures. The main

results presented here are also contained in [118]. The fundamental goal is to verify that the performance of each PMT at CT (in terms of noise and signal amplification) meets the requirements for a successful operation in the detector. The typical response of each PMT is carefully characterized and kept as reference in order to detect possible deviations in the PMT behaviour during the operation. Also, the impact of the cryogenic conditions on the PMT response is studied.

5.2.1 Testing setup

The testing facility at CIEMAT laboratory allows the measurement of the response of 10 PMTs at the same time. The test bench includes of a 300-l vessel where the PMTs are inserted. The vessel at atmospheric pressure is fed with liquid nitrogen (LN_2) at 77 K for the cryogenic tests through a pipe from a 400-l tank at 2 atm of pressure. An automatic filling system based on electro-valves, temperature sensors and level probes is designed to be controlled through a PC. A picture of the dewar and a diagram of the cryogenic setup can be seen in Figure 5.1.

The PMT distribution inside the vessel is shown in Figure 5.2: there are two levels, with five PMTs per level, fixed to an internal structure that hangs from the dewar lid. The vessel is opened and closed using a little crane. Different CF40 ports are used for the cables, sensors and fibers to pass through. The 21-m HV-signal cables and the PMT support structures are the final ones installed in ProtoDUNE-DP.

More details on the test bench are given in Figure 5.3. The electronics covers the different planned measurements: dark current, gain and linearity. Further explanation on these PMT features will be given in the next section. Several VME and NIM modules are arranged. A V895 discriminator and V560 scaler tandem from CAEN¹ is employed to perform the dark current acquisition. For the gain and linearity measurements, a

¹<http://www.caen.it>

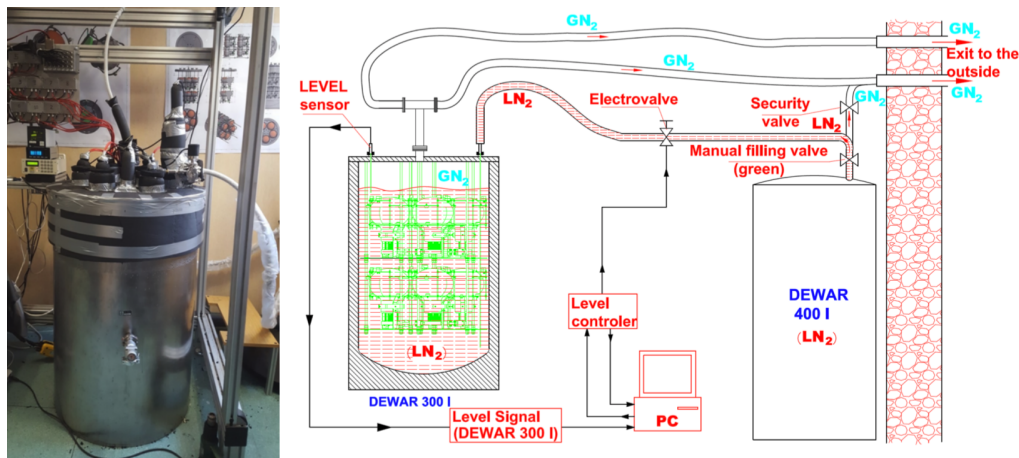


FIGURE 5.1: Left: 300-l vessel where the 10 PMTs to be tested are inserted. Right: Diagram of the cryogenic setup for the PMT characterization.

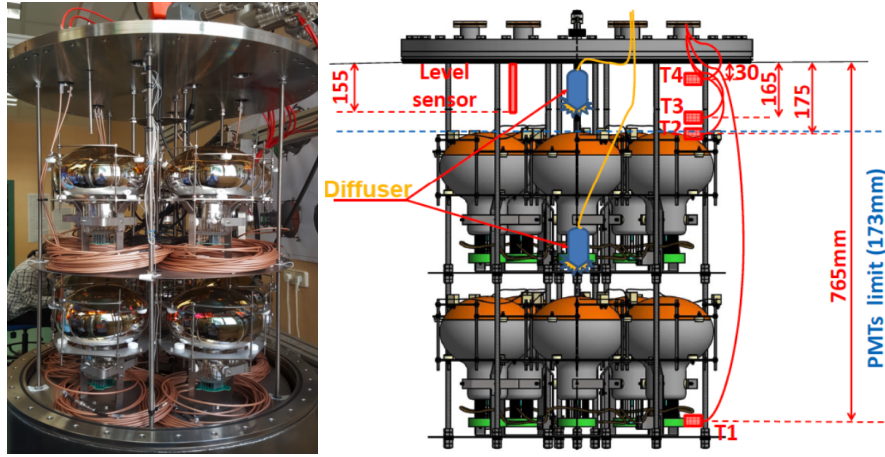


FIGURE 5.2: Left: Picture of the two PMT-levels in the internal structure, with the final 21-m HV-signal cables around them. Right: Schematics of the distribution of the 10 tested PMTs, temperature probes (T1-T4), diffusers, and level sensor inside the dewar.

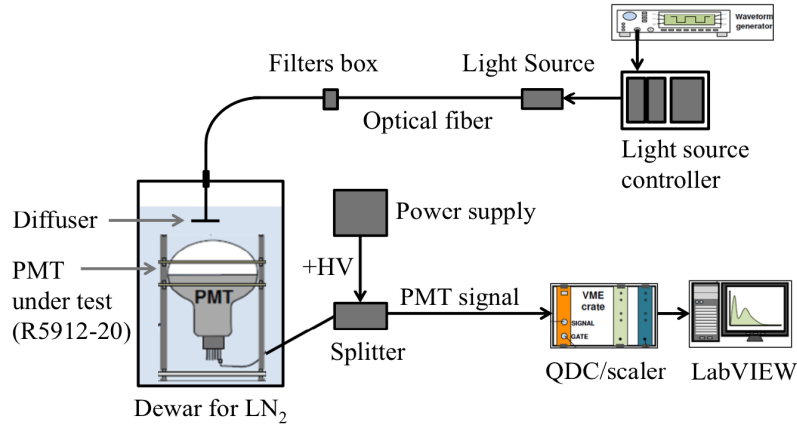


FIGURE 5.3: Diagram of the PMT testing experimental setup.

V965 CAEN Charge-to-Digital Converter (QDC) is used configured for a 200-ns window acquisition. A N1470 power supply from CAEN provides the HV to the PMTs and the DAQ is remotely controlled with LabView software².

As main light source, a PicoQuant GmbH³ laser head (405-nm wavelength and <500-ps FWHM) is exploited, and the amount of light can be tuned thanks to a set of 11 optical filters with different attenuation factors. The light source is synchronized with the QDC using a two-output-signal generator. Hard clad silica multimode optical fibers are selected for the light transmission to inside the vessel, and two diffusers are needed for a uniform illumination on the two PMT-levels.

²<http://www.ni.com>

³<https://www.picoquant.com>

5.2.2 Measurements

5.2.2.1 Dark Current

The dark current (DC) is defined as the PMT response, in absence of light, being the thermionic emission the main contribution at RT [139]. Nevertheless, at CT a non-thermal contribution significantly increases the DC rate [154, 155]. In the characterization, the DC is obtained from the average rate of signals over a threshold of 7 mV detected by the PMT in complete darkness. The threshold level is chosen to assure the trigger on single photo-electron (SPE) signals at a gain of 10^7 .

Once the PMTs are installed and the vessel is closed, the DC measurements at RT are started after at least 15 h of darkness. In the case of cryogenic conditions, a minimum time of 3 days is waited after the PMTs are immersed in the liquid before the DC measurement. Figure 5.4 shows that the DC drops more than one order of magnitude due to the previous ambient light exposure and, then, it becomes fairly stable with a small increase from the gain increment (see Figure 6.20).

The DC is measured doing a HV scan from 1000 V to 1900 V in 100 V steps. An additional DC measurement is taken at a gain of 10^9 at RT in order to compare with the reference value given by the manufacturer. However, it must be taken into account that Hamamatsu performs the DC measurement setting the threshold at the SPE level for a 10^9 gain, which is a higher threshold than the one mentioned before.

5.2.2.2 Gain

The PMT gain is the number of photo-electrons (PE) recorded at the anode (end of the dynode chain) per photon hitting the photocathode. In order to determine the value of this amplification, the PMT is illuminated with a small amount of photons to obtain the so-called SPE spectrum. Then, the spectrum is fitted to a convolution of a Poisson distribution

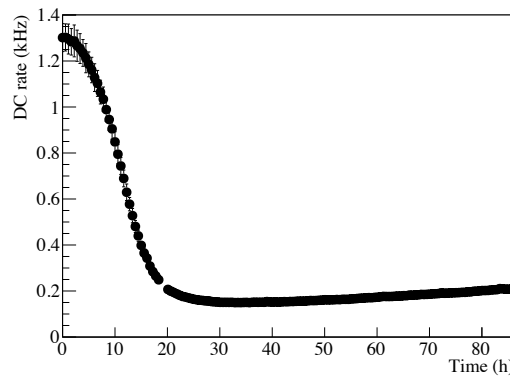


FIGURE 5.4: DC rate evolution with time right after immersing a PMT in LN_2 and closing the vessel. The DC is acquired every 10 s and averaged every 13 min in the plot; the vertical error bars correspond to the RMS.

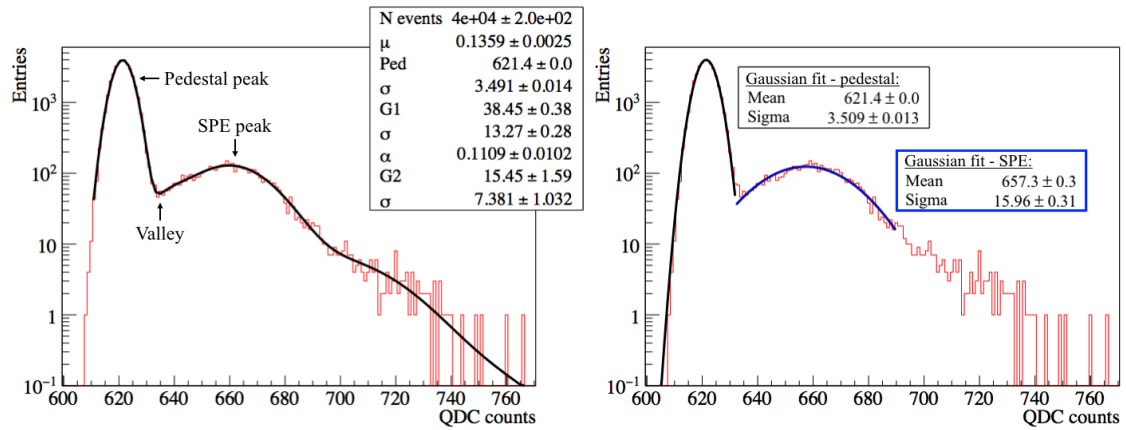


FIGURE 5.5: SPE spectrum (red) for a PMT at 1500 V. Left: Complete fit (black). Right: Fit to two Gaussian functions: one for the pedestal (black) and one for the SPE (blue).

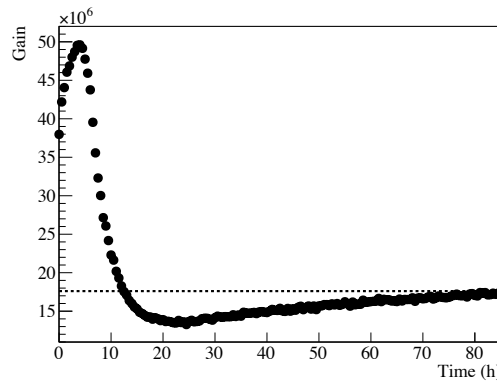


FIGURE 5.6: Gain evolution with time right after immersing a PMT in LN_2 and closing the vessel. Gain is obtained every 30 min. The nominal gain reached after 3 days is indicated with a dotted line. A similar gain behaviour is reported in [119].

and a binomial distribution. The former function models the number of PE generated in the photocathode while the latter takes into account two possible amplification paths: through the first dynode and directly starting in the second one [156].

Figure 5.5 left shows an example of a fitted SPE spectrum. The fit function relies on nine parameters (displayed in the legend) and successfully fits the valley of the spectrum (region between the pedestal and the SPE peaks), which is populated by badly amplified PE and/or spurious small signals. As it can be seen in the distribution, the charge collected in the anode is measured in QDC counts after the integration of the PMT pulse by the QDC in 200 ns. The parameter G_1 from the fit is scaled by a factor (including the QDC resolution and the electron charge value) to compute the amplification gain.

The same SPE spectrum but fitted using two Gaussian functions is presented in Figure 5.5 right: one modeling the pedestal peak and one modeling the SPE bump. The previous G_1 quantity can be obtained in this case as the difference between the mean values from the two Gaussian fits. This simpler approach does not fit the valley region, which cannot be correctly modelled by the complete function in some cases. However,

the gain determination with two Gaussians can be biased if the SPE spectrum is affected by the contribution of a second PE amplified in the dynode chain (third bump in the distribution).

The systematic comparison of the gain obtained with the two methods in the HV range from 1100 V to 1700 V shows that the gain from the two-Gaussian fit is about 4% higher, on average, than the one from the complete fit. However, the discrepancies found at gains 10^7 and 10^9 are 0.8% and 0.6%, respectively. Thus, both fits are considered suitable for the gain determination at the usual operating conditions and will be equally performed in the analyses presented in this thesis.

The gain-voltage curve (gain vs. HV) is measured from 1100 V to 1900 V in 100 V steps. Next, a fit is done following the power law $G = A(HV)^B$ being A and B constants that depend on the number, structure, and material of the dynodes [139]. Once the gain-voltage curve of a PMT is obtained, the required HV for a certain gain can be extrapolated or interpolated.

The gain evolution with time at CT is also investigated to determine the minimum time required for an stable gain measurement. Figure 5.6 illustrates the evolution for one PMT right after it is immersed in LN_2 . First, the gain increases as the PMT vacuum improves (~ 5 h). Then, it drops by a factor of 4 due to the PMT cooling (~ 10 h). Lastly, a small increase is observed and the gain reaches a stable value after ~ 3 days. Thus, 3 days is the minimum time waited after the immersion before starting the gain measurements.

5.2.2.3 Fatigue effect

The fatigue [157] is a saturation effect on the gain that occurs when the PMT output current increases. This effect is only observed in cryogenic conditions because the PMT recovery is much slower. The causes of fatigue can be: 1) high gain, 2) high light intensity, 3) high light rate, and 4) a combination of the previous causes. If the PMT response presents fatigue during the characterization, the results are distorted. Therefore, special care must be taken to prevent the fatigue or to assure the PMT has recovered from it between measurements.

The gain reduction and the recovery time depends on the amount of current generated and vary from one PMT to another. The plots in Figure 5.7 summarize the fatigue investigation at CT:

- Figure 5.7 top-left: gain evolution after operation at high gain. The gain evolution at 1400 V is studied after a gain measurement at 1900 V. Although the light level is low (SPE), the output current is high enough to reduce the effective PMT gain by 30% and the recovery takes about 12-24 h.
- Figure 5.7 top-right: gain evolution after high light intensity. When the PMT is exposed to ~ 1000 PE and operate at a gain of 10^8 , a similar behaviour to the one after high gain is observed.

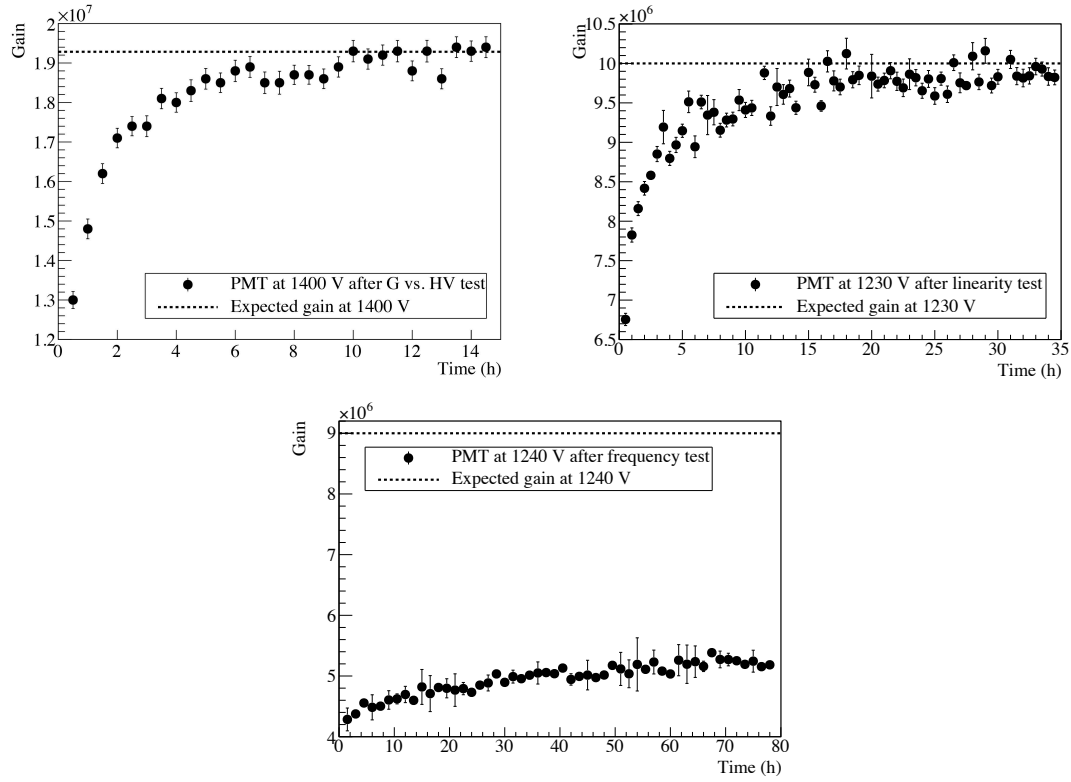


FIGURE 5.7: Top-left: Gain vs. time after reaching 1900 V. Top-right: Gain vs. time after linearity measurements. Bottom: Gain vs. time after high-rate measurements. In the three plots, the dotted lines represent the expected gains without fatigue.

- Figure 5.7 bottom: gain evolution after high pulse rate. For light signals at a frequency of $\sim$ MHz, a more permanent effect appears. In the plot, the gain decreases by a factor of 2. Some PMTs present a gain that is still 40% lower than the expected value after one week while others are totally recovered after 3 days.

In the aforementioned studies on the PMT fatigue, the gain monitoring is done triggering with low light level (SPE) at a rate of 100 Hz. The theoretical maximum output current of the PMT during the tests done before the gain evolution studies is calculated as:

$$I_{out} = e^- \cdot G \cdot npe \cdot f \quad (5.1)$$

where e^- is the electron charge, G is the PMT gain, npe is the average number of PE, and f is the light pulse rate. The current results for the high gain and high light intensity tests are a few μ A, whereas for the light rate test the obtained current is of hundreds of μ A. Therefore, the maximal output current seems to be proportional to the observed recovery time.

5.2.3 Characterization results

Figure 5.8 left presents the CIEMAT-Hamamatsu correlation for the DC rate measured at a 10^9 gain at RT. A good agreement is obtained in general. Figure 5.8 right shows the DC distributions at RT and CT for the 40 PMTs at a gain of 10^7 . On average, the results obtained are 0.4 ± 0.2 kHz at RT (always below 1.4 kHz), and 1.7 ± 0.3 kHz at CT (up to 2.5 kHz in some cases). No correlation between DC at RT and CT is observed. The DC rate as a function of the HV is measured at RT and CT for the 40 PMTs and Figure 5.9 shows the typical plots obtained for one of them. In general, the DC at CT is higher than at RT for the same gain. For this particular PMT, the DC increases from 0.6 kHz at RT to 1.9 kHz at CT for a gain of $1.5 \cdot 10^7$, being the behavior of this PMT representative of other PMTs.

Concerning the gain characterization, Figure 5.10 left illustrates the CIEMAT-Hamamatsu comparison of the HV required for a gain of 10^9 at RT, where the CIEMAT value is extrapolated from the gain-voltage curve of each PMT (example in Figure 5.10 right). Despite the differences in the setup and the method to determine the gain, the correlation is fairly good with a small deviation of about 2.3%. On the other hand, Figure 5.11 contains the results on the HV required for a gain of 10^7 at RT and CT (CIEMAT results). As expected, a higher HV is needed at CT (170 ± 72 V, on average) and the gain drop at CT with respect to RT is $71 \pm 14\%$, on average.

Thanks to the characterization, two defective PMTs were identified: one had no signal and the other had a DC rate of around 100 kHz (almost 60 times the reference value given by the manufacturer). These PMTs had to be replaced by new ones. Note that in the previous plots, the results of the replacements are shown. In addition, seven PMTs showing very unstable DC rate in time (i.e. large error bars in Figure 5.8 left) were inspected by Hamamatsu, albeit no defects were found. However, the four of them with highest DC rate were designated as spares.

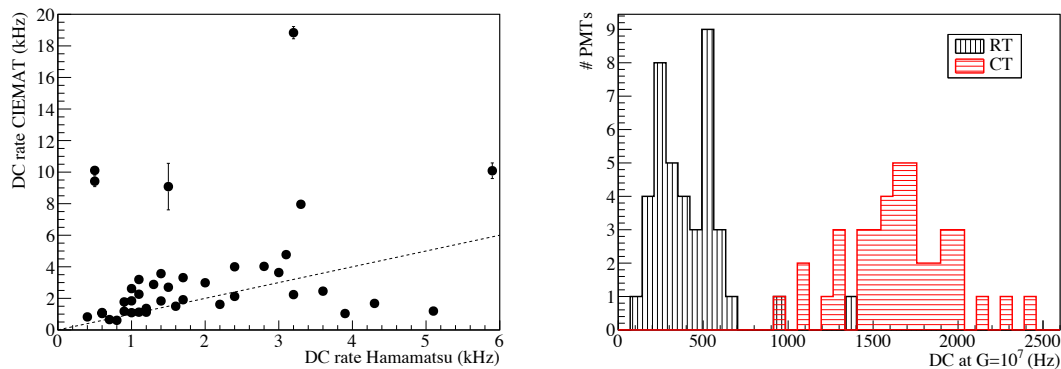


FIGURE 5.8: Left: DC measured at CIEMAT vs. Hamamatsu for a 10^9 gain at RT. DC is measured every 10 s during 5 min, and the error bars represent the RMS of the average value. The dotted line corresponds to the identity line. Right: DC distributions for a 10^7 gain at RT and CT measured at CIEMAT for the 40 PMTs (0.4 ± 0.2 kHz at RT and 1.7 ± 0.3 kHz at CT, on average).

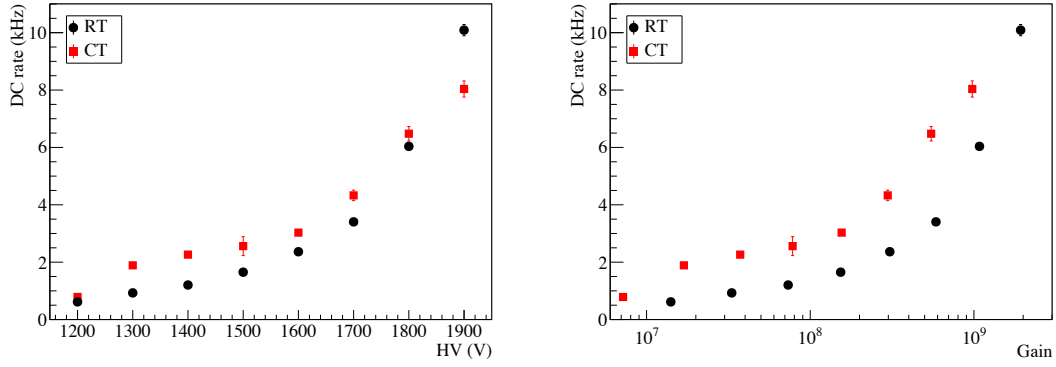


FIGURE 5.9: Left: DC vs. HV at RT and CT for one PMT. Right: DC vs. gain at RT and CT for one PMT. For each HV, DC is measured every 10 s during 5 min, the average value is plotted and the error bars represent the RMS.

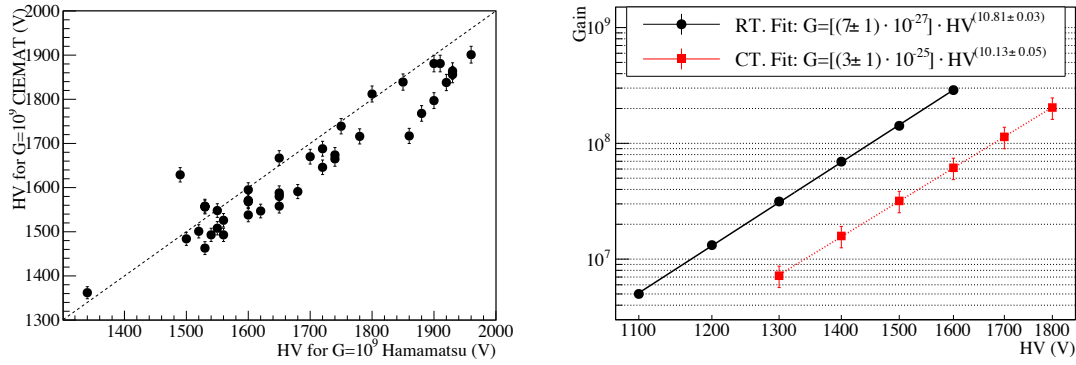


FIGURE 5.10: Left: HV required for a gain of 10^9 at RT according to CIEMAT and Hamamatsu for the 40 PMTs. The dotted line corresponds to the identity line. Right: Gain-voltage curves for one PMT at RT and CT. The dots represent the measurements and the lines correspond to the power-law fit. The vertical error bars are the average gain variation obtained from repeated measurements: 7% at RT and 21% at CT.

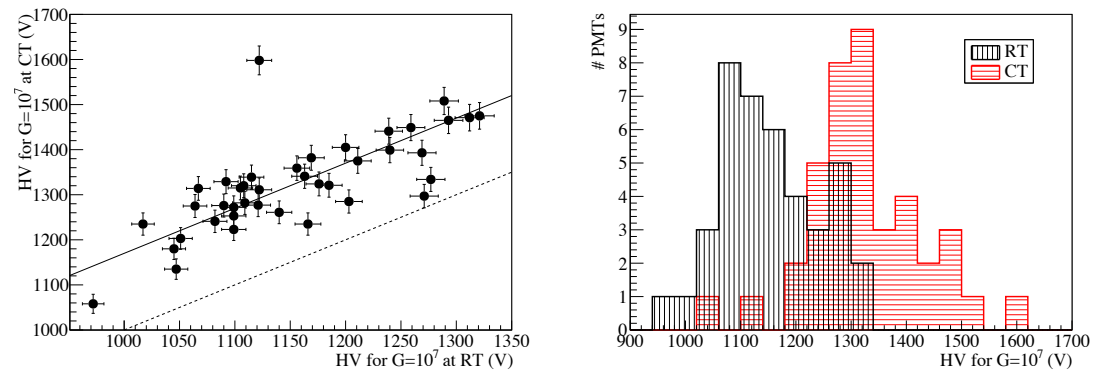


FIGURE 5.11: Left: HV at RT vs. CT for a 10^7 gain measured at CIEMAT for the 40 PMTs. The dotted line corresponds to the identity line and the solid line the identity line shifted 170 V. Right: Distributions of the HV required to obtain a 10^7 gain at RT and CT (1154 ± 87 V at RT and 1324 ± 103 V at CT, on average).

5.3 Study of PMT linearity in cryogenic conditions

As commented in the previous chapter, the same or similar large-area PMT model selected for ProtoDUNE-DP has been also employed in other LAr detectors such as MicroBooNE [119], ICARUS T600 [120], MiniCLEAN [140] and ArDM [141]. However, some aspects of the PMT performance at CT, like the gain instability with time, are not completely understood. Thus, further investigation on the PMT behaviour in cryogenic conditions has been carried out. Note that the specifications provided by the manufacturer only concerns the device performance at RT. The PMT linearity tests at CT presented in this section are also contained in a publication [118].

The setup used for the PMT characterization (see Section 5.2.1) is also employed for these measurements. Besides the laser (405-nm wavelength and <500-ps FWHM), an LED pulser (460-nm wavelength and 40-ns pulse width) is also employed as light source to study the impact of the pulse profile on the PMT response. The different pulse shape from each light source is evident in the waveforms displayed in Figure 5.12.

5.3.1 Measurements

5.3.1.1 Linearity with the light intensity

In ProtoDUNE-DP, the amount of scintillation light reaching the PMTs vary from a few PE to thousands of PE, depending on the particle energy and the track topology. Thus, a wide dynamic range with PMT linear response is desirable. The PMT linearity is studied at gains up to 10^8 and using the set of optical filters to regulate the light intensity, going from low to high light levels (from SPE regime up to ~ 1000 PE) to prevent and minimize the fatigue effect. Three filters corresponding to the linear region are taken as references (measured $\sim$ expected in terms of light) and the transmission factors of the others are used to estimate the expected amount of light. For low intensity illumination (SPE level), the average number of PE is obtained from the fit of the SPE spectrum, but it is not used as reference due to its large uncertainty.

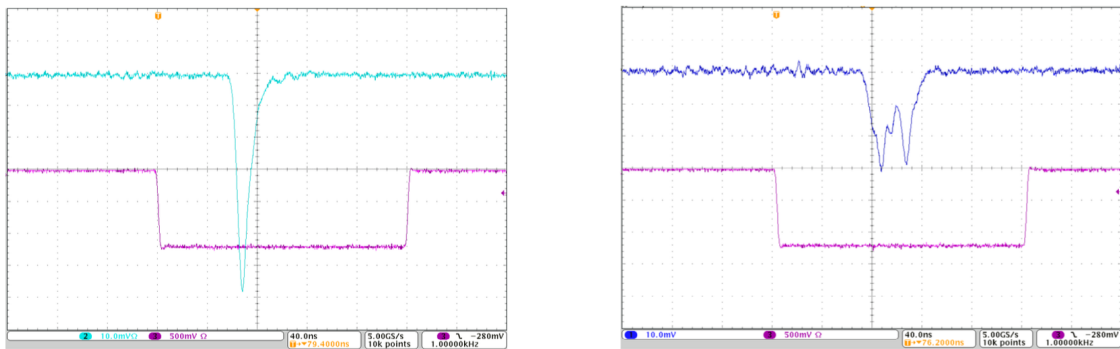


FIGURE 5.12: PMT response to a ~ 10 -PE light pulse from the laser (left) and the LED (right), in blue. The 200-ns integration window is indicated in purple.

It is known that the deviation from the linear response is mainly caused by the anode saturation. The PMT response to the 405-nm laser (<1 -ns pulse) and the 460-nm LED (<40 -ns pulse) are compared in order to check the effect of the pulse profile. For the same amount of detected light, the shorter the light pulse, the higher output peak current leading to a more easily PMT saturation (space-charge effects on the last dynodes).

5.3.1.2 Linearity with the pulse rate

The PMT response to different light pulse emission frequencies (from 100 Hz to 10 MHz) is investigated in the laboratory trying to reproduce the continuous background of S2 light pulses in ProtoDUNE-DP. The goal is to ensure a good PMT performance in such conditions. The frequency scan is performed for different light intensities: from ~ 10 PE to ~ 50 PE. Again, laser and LED are compared. For each setup configuration, the charge spectra of the PMT is obtained to calculate the average amount of light detected by the PMT.

The average output current is proportional to the rate of the light pulses. As the base design is based on resistors, the PMT inter-dynode voltages have a dependency with the PMT output current. Therefore, the PMT response becomes not linear when the light rate increases over a certain limit. The current through the base resistors has two components: 1) the polarization current (constant and provided by the power supply), and 2) the PMT output current (going through the resistors in the opposite direction).

As the power supply keeps constant the total voltage applied to the base, a decrease on the last dynodes voltage (by the increase of the output current) makes higher the voltage on the first dynodes, increasing the PMT gain. If the voltage on last dynodes continues decreasing (by the increase of the output current) at some point this voltage is not enough to maintain the current flow to the anode, and it decreases following the typical I-V curve of a vacuum diode. In addition, the PMT output current does not depend on the light input intensity anymore but only on the light rate that is changing the voltage on the last dynodes.

5.3.2 Linearity results

Firstly, results on the light intensity impact are discussed. Figure 5.13 presents the PMT response as a function of the light intensity for three PMTs at RT using the laser. The vertical error bars correspond to 4% (from the gain variation obtained fitting spectra at different light levels) and the horizontal ones are 9% (from error propagation of the uncertainties in the gain estimation and in the measurement of the transmission of the filters). The observed behaviour in all the tested PMTs was the same, as it reflects the good agreement among the PMTs shown in the plot. For gains below 10^6 , the linearity is preserved in all the tested range (up to ~ 1000 PE). On the contrary, the plot shows that for gains close to 10^7 , the PMT remains linear only up to 200 PE, while for larger gains (10^8) the linearity is already lost with 75 PE.

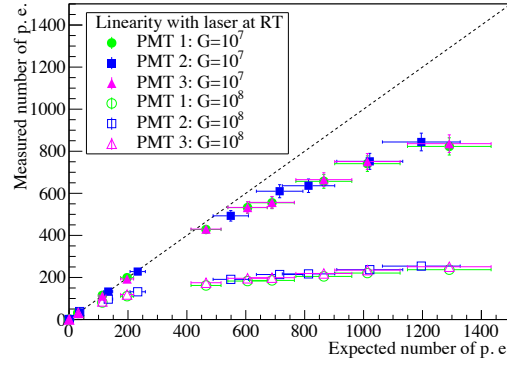


FIGURE 5.13: Measured vs. expected light for three PMTs at RT illuminated with the laser.

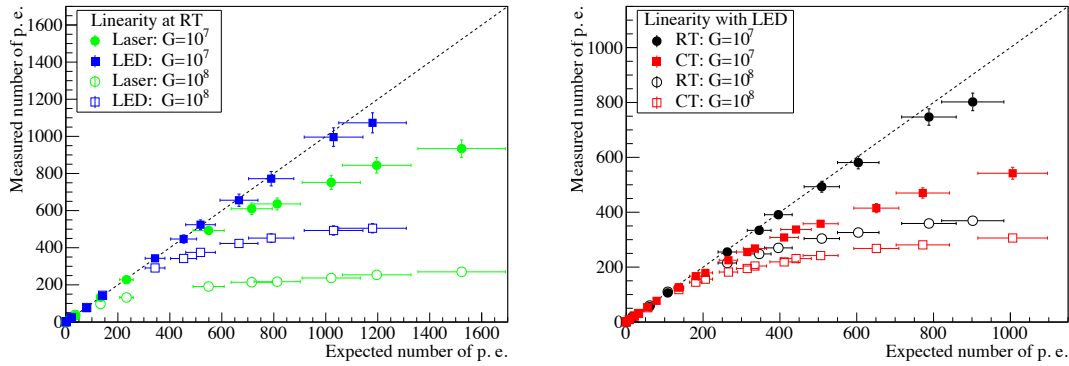


FIGURE 5.14: Left: Measured vs. expected light with the LED and the laser at RT. Right: Measured vs. expected light at RT and CT for the LED.

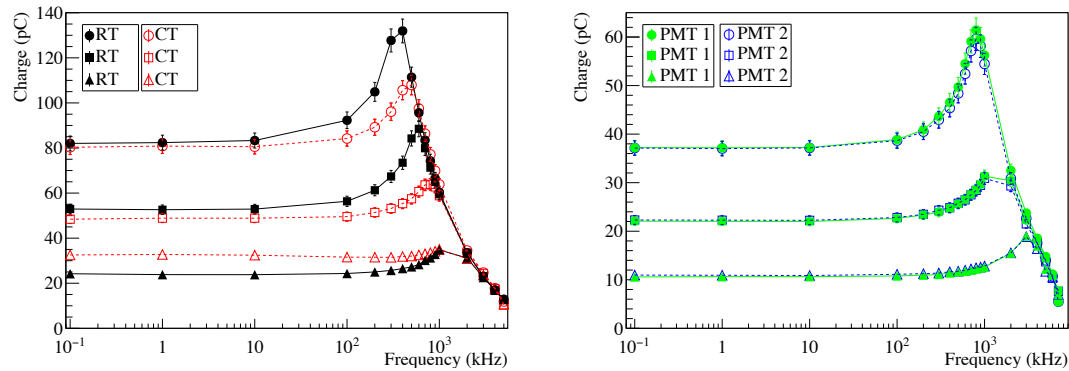


FIGURE 5.15: Left: PMT response to the LED frequency at RT and CT. Right: Response of two PMTs to the laser frequency at RT. The vertical error bars are 4% from the variation of the charge when repeating the measurements.

The responses of one PMT at RT with laser and LED illuminations are compared in Figure 5.14 left. The linearity range expands when the light source has a wider pulse (LED), showing a clear dependency on the pulse shape. In Figure 5.14 right, the linearity with the LED is studied comparing RT and CT measurements: the linear range at CT is shorter than at RT. Therefore, despite the very good linearity at RT, the PMT response

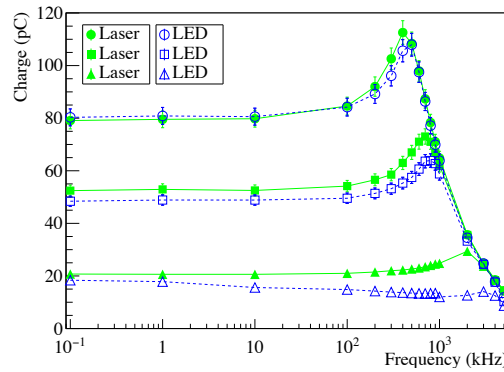


FIGURE 5.16: Charge vs. frequency for LED and laser at CT. The vertical error bars are 4% from the variation of the charge when repeating the measurements.

is saturated at 300 PE for a 10^7 gain at CT. In the case of the laser, similar studies were performed but the worse linearity at CT than at RT is less evident.

Secondly, results on the PMT response vs. the pulse frequency are summarized here. Three regions can be clearly observed in Figure 5.15 left: 1) linear PMT response until a given frequency (~ 10 kHz) which depends on the charge, 2) over-linearity region where the PMT gain increases, and 3) saturation region (> 500 kHz) when the voltage between the last dynode and the anode is close to zero and the PMT output decreases with the light rate. The PMT output is never zero because the initial velocity of the PE is not zero. At CT, the fatigue effect observed (gain reduction) compensates the beginning of the gain increase with the light rate leading to a small reduction of the over-linearity region. The same saturation curve is expected both at RT and CT because it only depends on the base design. In Figure 5.15 right, the good agreement between different PMTs can be observed.

Figure 5.16 compares the response to laser and LED frequencies. The results suggest a very similar response but with the over-linearity region starting at slightly higher frequencies with the LED (wider pulses with smaller output peak current). The PMT response is linear until ~ 1 MHz for low intensity signals (similar to the expected S2 background).

5.4 Over-pressure PMT tests

Dedicated PMT tests have been carried out to prove that the selected PMT model supports the pressure expected not only in ProtoDUNE-DP (with PMTs at the bottom of the cryostat under 6-7 m of LAr) but also in a larger detector as the proposed DUNE DP FD (under 14 m of LAr, at 3-bar absolute pressure), without showing any mechanical or electrical damage. It has to be noted that, despite validating the PMT to operate up to 7 bar at RT, Hamamatsu does not perform any test in both CT and over-pressure. These measurements are neither found in the literature. Gain and DC are measured at 4-bar absolute pressure to

study the PMT behaviour. More details on these particular tests are given in a publication on this topic [152].

Some potential risks of the over-pressure operation are a vacuum loss (causing the malfunctioning of the device), and, in the worst case, a glass break which would have terrible consequences in the detector [159]. In order to avoid the PMT implosion, other experiments [160, 161] enclose the PMT into a shielding structure. However, this solution is not valid for DUNE because the VUV light from the LAr scintillation would be absorbed by the shielding system.

5.4.1 Measurements

The tests were done at CT using the same setup as for the PMT characterization (see Section 5.2.1). A 50-l vessel for individual PMT testing in LN₂ was employed instead of the 300-l vessel used to test 10 PMTs at once. The over-pressure is created by the evaporated nitrogen inside the 50-l vessel and controlled thanks to a back-pressure regulator. The LN₂ temperature at 1 bar (atmospheric pressure) is 77 K while at 4 bar (3-bar over-pressure) is 91 K. A diagram and a picture of the cryogenic setup for the over-pressure tests can be seen in Figure 5.17.

Four PMTs were tested in over-pressure conditions. The first three PMT were provided by Hamamatsu for these tests and have known defects (not affecting the results); the forth one is expected to have a regular behaviour:

- FA0169: high dark current and after-pulse rates.
- FA0175: peeling of evaporated aluminum on glass bulb.
- FA0187: low cathode sensitivity; gain instabilities were observed so it is only used as a mechanical sample.
- FB0019: previously characterized at CT, as explained in Section 5.2.

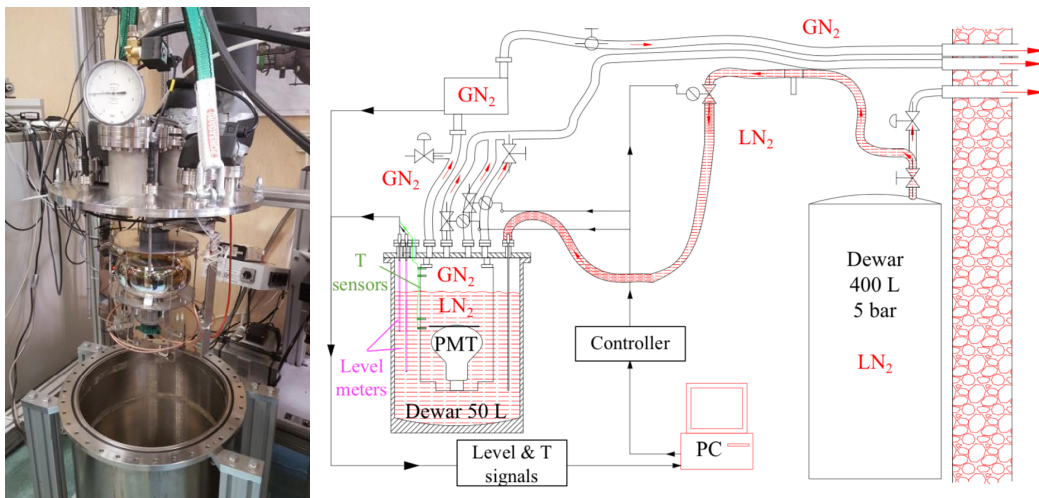


FIGURE 5.17: Left: Schematic drawing of the cryogenic setup for the PMT testing up to 4-bar absolute pressure. Right: Picture of the pressure testing setup.

The gain-voltage curve and the DC rate vs. HV are measured following the same procedures explained in Section 5.2. On the one hand, the PMT gain drops when the temperature decreases. On the other hand, the DC rate undergoes two effects when the temperature goes down: it increases due to non-thermal contributions [154, 155] but the gain reduction compensates that increment to some extent.

Approximately one week of data taking per PMT is needed. The first day (Day 1), the PMT is installed in the vessel with LN₂ and left for three days to allow the thermalization (Days 2 to 4), as it was done for the PMT characterization reported in Section 5.2. Then, gain and DC are measured at atmospheric pressure (Day 5). On the same day (Day 5), the pressure is increased from 1 bar to 4 bar in ~30 min and left overnight for the PMT thermalization. On the next day (Day 6), gain and DC measurements at 4 bar are performed, and the system is set back to 1 bar. On the last day (Day 7), gain and DC at 1 bar are measured again to ensure the PMTs did not suffered any damage. In addition, the gain-voltage curve at RT was taken afterwards for all the PMTs.

5.4.2 Results

Figure 5.18 presents the gain-voltage curves measured at each step for the three tested PMT. For the same HV and 1 bar of pressure, the gain at CT is lower than at RT. At CT, the

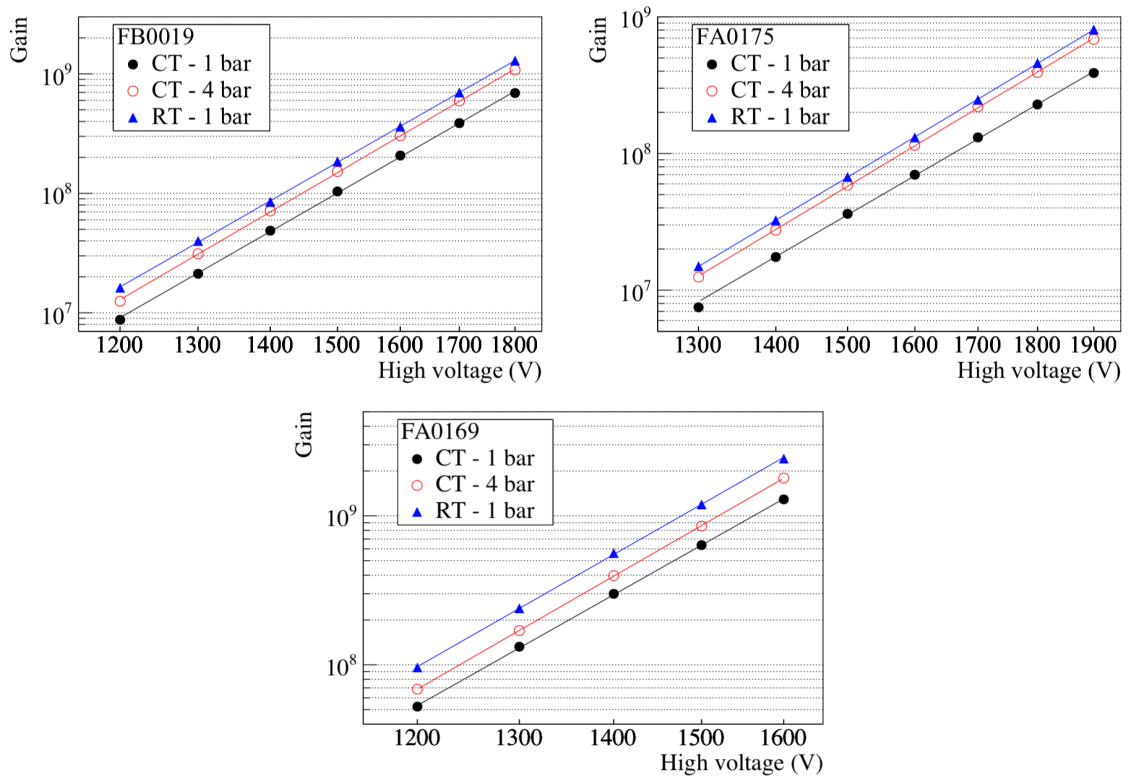


FIGURE 5.18: Gain-voltage curves at RT and at two CT (77 K and 91 K) for the three tested PMT. The dots represent the measurements (with errors from the gain fit) and the lines are the power-law fits.

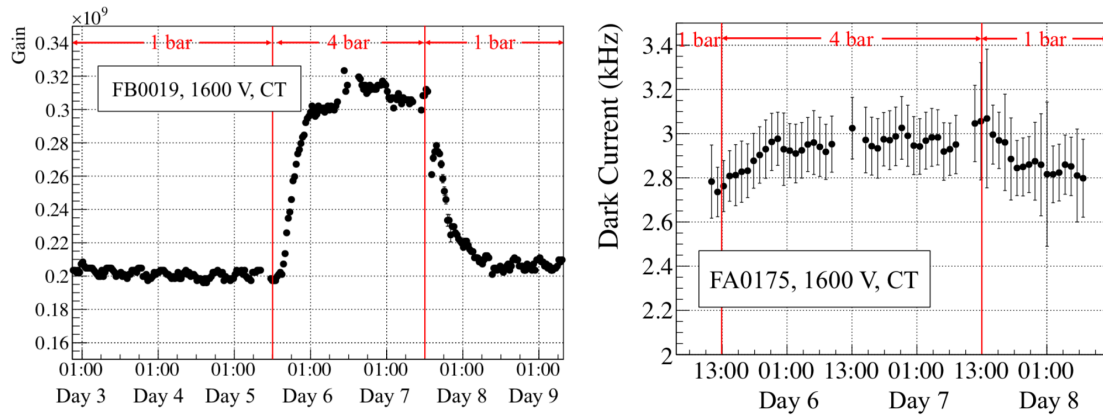


FIGURE 5.19: Left: Gain evolution with time for one PMT. Right: DC rate evolution with time for one PMT. In both plots, the pressure is increased from 1 bar to 4 bar on Day 5 at 13:00 h, and set back to 1 bar on Day 7 at 13:00 h.

PMT	HV (V)	P (bar)	T (K)	G	DC (kHz)
FB0019	1600	1	77	$2.0 \cdot 10^8$	2.93 ± 0.14
		4	91	$3.0 \cdot 10^8$	2.53 ± 0.15
FA0169	1500	1	77	$6.4 \cdot 10^8$	4.18 ± 0.15
		4	91	$8.6 \cdot 10^8$	4.10 ± 0.17
FA0175	1600	1	77	$6.9 \cdot 10^7$	2.78 ± 0.13
		4	91	$1.1 \cdot 10^8$	3.02 ± 0.14

TABLE 5.1: DC rate at a given HV for three PMTs at two pressures.

gain at 1 bar is lower than at 4 bar, due to the lower operating temperature. Being the operating gain 10^8 at RT (295 K), the gain decreases on average $46 \pm 1\%$ at CT at 1 bar (77 K), and $21 \pm 8\%$ at 4 bar (91 K), considering the three PMTs. Consistent results were obtained from repetitive measurements on the same PMT.

The gain evolution during the pressure cycle at CT is shown in Figure 5.19 left for one PMT. Gain increases with pressure and the value at atmospheric pressure is recovered. It can be observed that the gain stabilization takes around 12 h. The DC rate evolution is reported in Figure 5.19 right for a PMT. No effect on the DC rate due to the pressure change is observed and no anomalies are found. Since the DC depends on both the temperature and the PMT gain, and the two effects go in opposite direction, no big change in the DC is expected, as reported in Table 5.1.

None of the four PMTs presented any mechanical change and all three tested PMTs showed the expected performance, being the variations due to the change in the operating temperature. Hence, the PMT model is valid for operation at 4-bar absolute pressure.

5.5 LCS validation

The different stages of the ProtoDUNE-DP LCS validation are contained in a publication [151] and some of them (characterization of the external system at RT and CT, and tests with the complete chain at CT) will be reviewed in this section. The validation process aims at guaranteeing the good performance of the system before being installed in the detector. All the LCS components are tested at RT whereas the internal ones (eventually operating in LAr) are also measured at CT using LN₂ (77 K).

5.5.1 Inner-fiber and bundle characterization

As mentioned before, the inner components are tested both at RT and CT. A 460-nm LED (Nichia, NSPB300B) is connected directly to the fiber or bundle entrance and the light output of the individual fibers and bundles is measured with a powermeter (Ophir, PD300-UV) at the end of the fiber. In total, seven individual fibers and seven fiber bundles are measured (one fiber+bundle system is kept as spare). The different elements are immersed in a dewar filled with LN₂ at 77 K for the cryogenic measurements. The components are measured at RT to obtain a reference value and, after every test at CT, it is checked that the previous response at RT is recovered once the LN₂ has evaporated.

Figure 5.20 summarizes the results of the inner fiber characterization. The relative power outputs at RT and CT are plotted with respect to the average at RT. The light uniformity among fibers turns out to be >90% and the light attenuation at CT with respect to RT is 0.8 ± 0.2 dB. A shorter fiber was also measured to study the transmission variation due to the length. It was found that the light attenuation from 1 m to 22.5 m is 1.0 ± 0.3 dB at RT. This result is compatible with the expected attenuation from Thorlabs specifications: 1.35 dB at RT.

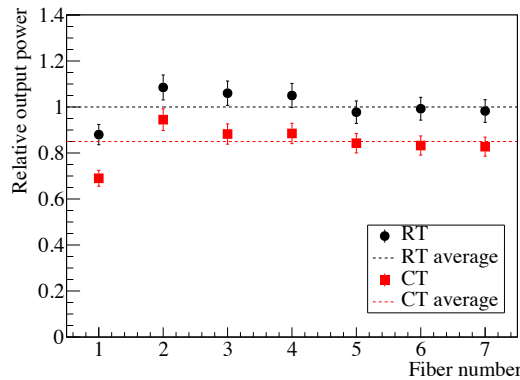


FIGURE 5.20: Characterization results of the 22.5-m fibers at RT and CT. The error bars correspond to the 5% systematic error obtained from repetitive measurements. The power output is shown relative to the average value at RT.

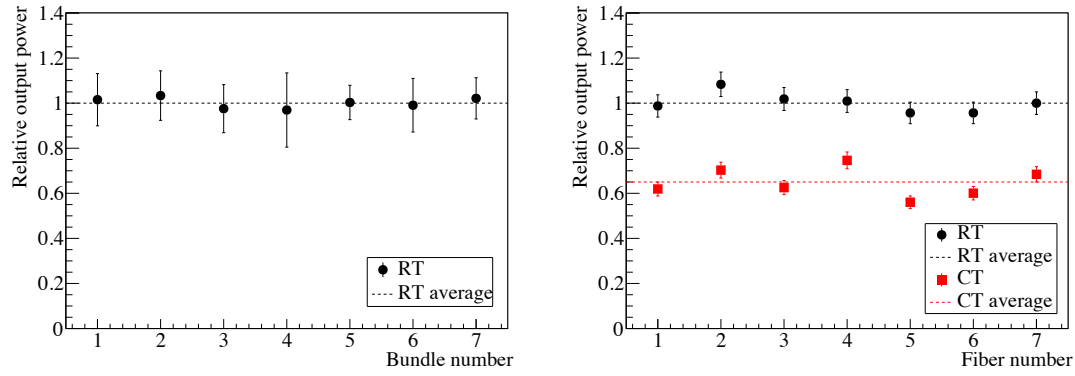


FIGURE 5.21: The power output is shown relative to the average value at RT. Left panel: Characterization results of the 1-to-7 fiber bundles at RT. In this case, the error bars correspond to the dispersion among fibers of the same bundle (about 11%). Right panel: Characterization results of one bundle (#2) at RT and CT (individual fiber results are given). In this case, the error bars are the 5% systematic variation obtained from repetitive measurements.

Component(s)	Attenuation at CT wrt RT (dB)
22.5-m fiber	0.8 ± 0.2
3-m bundle	1.9 ± 0.3
MS	0.4 ± 0.2
22.5-m fiber + MS + 3-m bundle	3.1 ± 0.3

TABLE 5.2: Relative attenuation results at CT from the individual characterization of the inner components.

The fiber bundles were characterized in a similar way. On the one hand, the relative power outputs of the 7 bundles at RT are presented in Figure 5.21 left, where the dispersion among fibers of the same bundle is contained in the error bars. On the other hand, for one bundle, the relative power outputs of each fiber at RT and CT are shown in Figure 5.21 right. It is concluded that a good homogeneity is observed among bundles and also among fibers of each bundle since the light uniformity is $\sim 90\%$. The light attenuation at CT with respect to RT is 1.9 ± 0.3 dB. Moreover, the results are compared to the performance of a shorter bundle. In this case, the transmission variation at RT from 3 m to 1 m is negligible as expected since according to Thorlabs specifications it should be ~ 0.15 dB.

The light loss at CT due to the fiber-bundle connection through a vacuum compatible SMA to SMA mating sleeve (MS) is investigated. Two measurements are done: 1) the complete fiber+MS+bundle system at CT, and 2) the system at CT except for the MS which is at RT (outside the dewar). The light attenuation at CT with respect to RT caused by the fiber-bundle connection itself is 0.4 ± 0.2 dB. In addition, the complete system at RT was also measured to obtain the attenuation at CT with respect to the operation at RT: 3.1 ± 0.3 dB.

#	Component	Attenuation (dB)	Reference
1	MS (flange)	<1.5	Manufacturer specifications
2	22.5-m fiber	1.0±0.3	Section 5.5.1
3	MS	<1.5	Manufacturer specifications
4	Geometry	12	Equation 5.2
5	3-m bundle	0	Section 5.5.1
6	CT operation	3.1±0.3	Table 5.2
7	Total at RT	<16.0±0.3	#1 + #2 + #3 + #4 + #5
8	Total at CT	<19.1±0.4	#7 + #6

TABLE 5.3: Estimated light attenuation of the inner system.

Table 5.2 includes the aforementioned attenuations corresponding to each component and also the measured attenuation of the complete inner chain which is consistent with the sum of the individual component attenuations (3.1±0.4 dB).

5.5.2 Expected light attenuation (inner system)

The total light attenuation of the inner system must take into account the fibers, the connectors, the cryogenic operation of the chain and also the geometrical efficiency at the fiber-bundle coupling. The geometrical factor, A_{Geo} , which accounts for dividing the light from one to seven fibers, dominates the attenuation of the inner system and is obtained as follows:

$$A_{Geo} = -10 \cdot \log \left(\frac{S_{200}}{S_{800}} \right) = -10 \cdot \log \left(\frac{0.031 \text{ mm}^2}{0.503 \text{ mm}^2} \right) = 12 \text{ dB} \quad (5.2)$$

where S_{800} and S_{200} are the surface of the 22.5-m fiber and the one of each fiber in the bundle, respectively.

The different contributions to the attenuation are included in Table 5.3. The total attenuation result at CT from the individual component characterization and the manufacturer specifications is <19.1±0.4 dB. Consequently, the LED must provide at the flange entrance a power about 80 times⁴ the desired one at the PMT photocathode, which is feasible given the LED operating range.

5.5.3 Validation of the full system

The performance of the full LCS in the laboratory was validated. Five PMTs were tested at the same time at CT using the setup of the PMT characterization (see Section 5.2.1). Pictures of the setup can be seen in Figure 5.22. All the LCS chain from the light source to the fiber pointing at each photocathode (final components of the LCS) is installed.

⁴The estimation is obtained using the relation $Att.[dB] = -10 \cdot \log(P_{out}/P_{in})$.

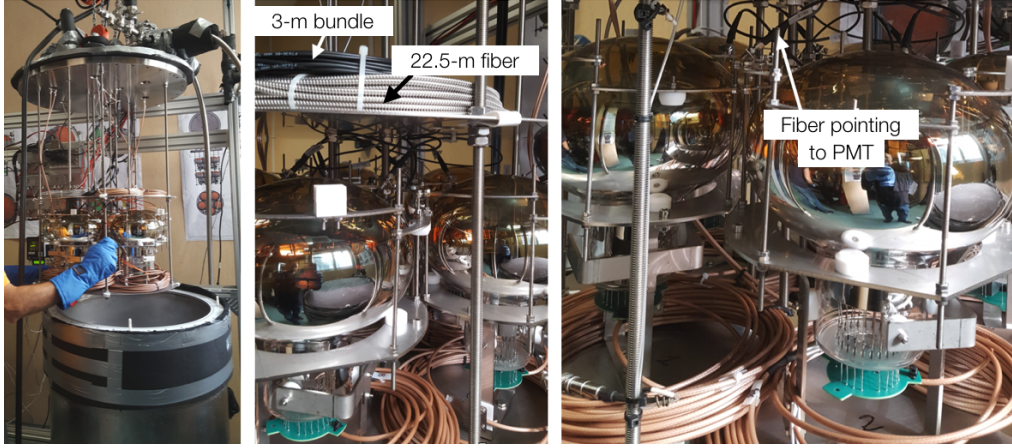


FIGURE 5.22: Pictures of the setup for the LCS validation with PMTs.

It corresponds to one of the six subsystems later installed in ProtoDUNE-DP. One LED provides simultaneously light pulses to the five PMTs so the gain and light linearity can be determined.

Two data taking campaigns were carried out: a first one with all the elements at RT and a second one with the inner components at CT. In both cases, the results are compared with the ones obtained using diffuse light and the original PMT characterization setup. Three measurements are performed: 1) gain at the operating HV (set for a target gain of 10^7), 2) the gain calibration curve, and 3) the PMT response beyond the SPE level. It must be noted that all the tests are done at a gain of 10^7 except the calibration curve acquisition.

5.5.3.1 Attenuation measurement with PMTs

One of the goals of the tests reviewed in this chapter is the measurement of the light attenuation from the flange to the PMT photocathode. The amount of light reaching the flange is quantified using the powermeter. Then, the number of photons is calculated from the measured power as:

$$\#ph = \frac{P \cdot t}{E} = \frac{P/f}{(h \cdot c)/\lambda} \quad (5.3)$$

where P is the power, f the frequency at which the LED is pulsed, h the Planck constant, c the speed of light, and λ the LED wavelength.

In order to include in the validation all the LEDs, one measurement per LED at the maximum voltage (19.5 V) is taken adjusting the LED position for the desired light output. The light range covered both at RT and CT goes from $\sim 40k$ to $\sim 80k$ photons at the flange.

5.5.3.2 Measurements at RT

The tests at RT are important to verify the good performance of the full system and the testing setup before going to cryogenic conditions. In particular, four LEDs were tested one by one.

First, the gain of each PMT is obtained from the fit of the SPE spectrum at the operating HV, following the procedure explained in Section 5.2.2.2 (see an example in Figure 5.23 left). An LED voltage of 6 V allows to illuminate the PMTs at the SPE level. The average of the gains obtained for the different LEDs is compared with the gain value obtained with diffuse light and the original characterization setup (at the same operating HVs). The average discrepancy (LCS setup vs. PMT characterization setup) for the five PMTs ($\sim 8\%$) is compatible with the expected uncertainty from the individual PMT characterization at RT ($\sim 7\%$).

Next, the charge collected by the PMTs for larger light inputs is studied. This kind of measurement can be interesting during the detector operation to confirm the optical path integrity, the relative changes of the PMT quantum efficiency or as an alternative method to determine the PMT gain [162]. Figure 5.23 right shows the average charge for the different LEDs and two LED bias voltages above the SPE level: 14 V and 19.5 V. The vertical error bars in the plots represent the dispersion among PMTs. On the one hand, it was checked that the charge difference among LEDs is due mainly to the LED positions in

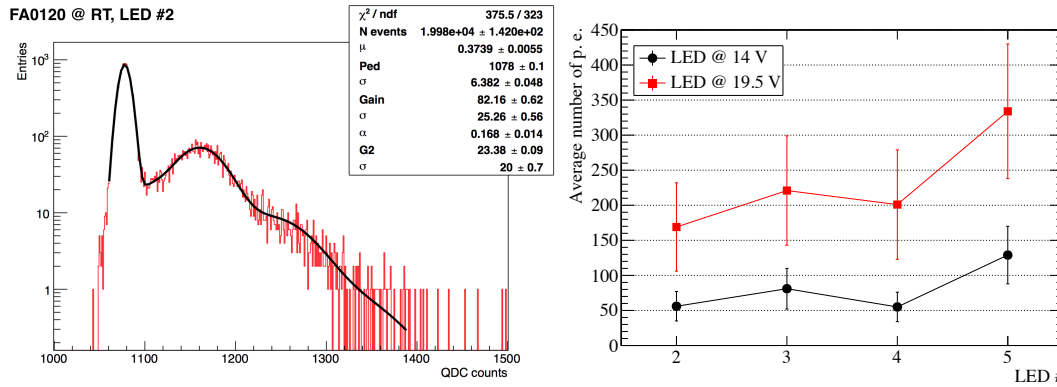


FIGURE 5.23: Left: Fit of the SPE spectrum taken at RT with the full LCS. Right: Average charge detected by the PMTs at RT with the full LCS for two light levels as a function of the LED.

Measured by PMTs		Expected (Table 5.3)
PE / photons (%)	Attenuation (dB)	Attenuation (dB)
0.41 ± 0.02	16.0 ± 0.2	$< 16.0 \pm 0.3$

TABLE 5.4: Measured attenuation by the PMTs (full system) and expected attenuation from the component characterization and the manufacturer specifications (Table 5.3), at RT for the inner fiber system. The measured attenuation is obtained taking into account a PMT quantum efficiency of 16.5%, value at RT and 460 nm measured by Hamamatsu for these particular PMTs.

the light guide structure that can be easily adjusted to equalize their responses. On the other hand, the average charge at RT detected by the PMTs operating at the maximum voltage (19.5 V) is about 230 PE.

The light attenuation at RT can be obtained from these measurements. The results are contained in Table 5.4, where the final result of 16.0 ± 0.2 dB is compatible with the expected attenuation given in Table 5.3. Moreover, the small error of the PE/photons ratio indicates that the transmission (or attenuation) is similar for different light inputs since it corresponds to the dispersion among four measurements (from 40 to 90 photons).

5.5.3.3 Measurements at CT

The same measurements performed at RT were done at CT, and also the SiPM performance and the calibration curves at CT were studied. The six LEDs were tested this time.

An example of fitted SPE spectrum at CT is shown in Figure 5.24 left. The average discrepancy between the gain determined with the LCS and with diffuse light is $\sim 7\%$, again below the expected spread from the individual PMT characterization at CT (21%). Therefore, the LCS allows to obtain well the PMT gain at CT.

In addition, the PMT response to different light levels (LED bias voltages) is evaluated (Figure 5.24 right). No difference in the collected light has been found due to the light

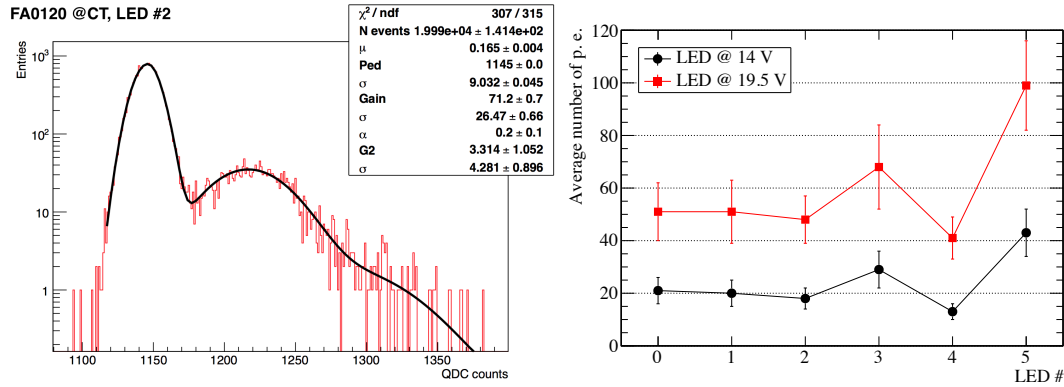


FIGURE 5.24: Left: Fit of the SPE spectrum taken at CT with the full LCS. Right: Average charge detected by the PMTs at CT with the full LCS for two light levels as a function of the LED.

Measured by PMTs		Expected
PE / photons (%)	Attenuation (dB)	Attenuation (dB)
0.12 ± 0.02	21.4 ± 0.7	$< 19.1 \pm 0.4$

TABLE 5.5: Measured attenuation by the PMTs (full system), and expected attenuation from the component characterization and the manufacturer specifications (Table 5.3), at CT for the inner systems. The measured attenuation is obtained taking into account a PMT quantum efficiency of 16.5%, value at RT and 460 nm measured by Hamamatsu for these particular PMTs. No difference in the quantum efficiency at CT is expected [163].

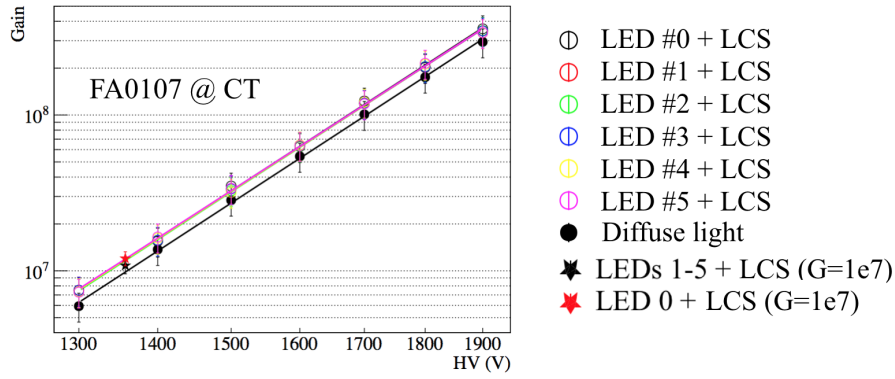


FIGURE 5.25: Gain calibration curves taken with the six LEDs and the full LCS (empty dots), and with diffuse light and a different setup (filled dots). The stars correspond to the gain measurement at the operating HV for a target gain of 10^7 . The average variation (along the HV range) between the LED+LCS results and the diffuse light curve is about 20%.

frequency (from 100 Hz up to 1 kHz). On average, the maximum light expected at the PMTs from the LCS at CT is about 60 PE (at 19.5 V, the maximum LED voltage), which is enough for the main goals of the system.

The light input at the flange has been controlled with the powermeter to obtain the light attenuation from that point to the PMTs. In Table 5.5, the result for the full LCS and the expected value from individual measurements at CT can be seen. In this case, the measured attenuation with the LCS is slightly larger than the expected one.

Last but not least, the gain calibration curves were successfully measured for the five PMTs and using the six LEDs. An example of the gain as a function of the HV for one PMT can be seen in Figure 5.25. As one can observe, a good agreement among the LEDs is achieved and the discrepancy with the diffuse light result (as in the PMT characterization) is within the expected 21%.

Concerning the SiPM testing, its response at 27.5 V has been measured by both the QDC and the built-in ADC of the BeagleBone. The difference observed between the charge detected by the two devices is $<5\%$, which validates the reference sensor.

In conclusion, the aforementioned results completely validate the LCS for its installation and operation in ProtoDUNE-DP.

ProtoDUNE-DP performance

“Failure is not the opposite of success;
it’s part of success.

— Arianna Huffington

6.1 Introduction

The construction and operation of ProtoDUNE-DP are landmarks in the history of the DP LAr detection technology. Valuable experience has been obtained for future large-scale detectors and the acquired expertise will be also exploited within the DUNE scheme. It is worth commenting that the WA105 demonstrator [84] was the largest DP LAr TPC ever built and operated until ProtoDUNE-DP and it provided useful feedback that allowed to anticipate different instrumentation problems and prepare solutions that greatly accelerated the ProtoDUNE-DP construction.

This chapter reviews some aspects related to the installation and operation of ProtoDUNE-DP, highlighting the milestones accomplished and technical issues encountered in the process. The project timeline is presented in Section 6.2, covering the installation, commissioning and operation phases. Finally, the PDS and the LCS performances are discussed in Sections 6.3 and 6.4, respectively.

6.2 ProtoDUNE-DP timeline

Figure 6.1 shows the general timeline of the project with the main stages that will be described in this section: 1) installation, 2) purging and filling, 3) commissioning, and 4) operation and data taking. The detector was operated taking data from the interaction of cosmic rays over 15 months, from mid-June 2019 to mid-September 2020.

6.2.1 Installation phase

Inside the Neutrino Platform facility (EHN1), the exact emplacement of the ProtoDUNE-DP is called NP02. The construction of the detector took about two years (2017-2019). On the 13th of June 2019, the man-hole access was closed and the detector purging started. Some relevant activities during the installation phase at NP02 are listed in Table 6.1.

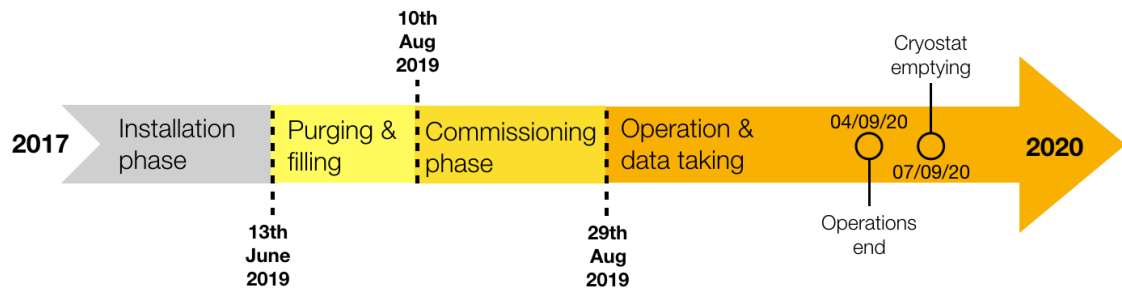


FIGURE 6.1: ProtoDUNE-DP general timeline.

Jan - Mar 2017	Installation of the outer NP02 vessel
Mar - Sep 2017	Thermal insulation and inner membrane construction
20 th Nov 2017	The cryostat declared as clean room
Jun 2018 - Jan 2019	CRP tests in the cold box
Sep 2018	Cathode installation
Feb 2019	PDS and CRP installation
Apr - May 2019	Completion of field cage and VHV installation
Jun 2019	Ground grid installation
13 th Jun 2019	Man-hole access closed

TABLE 6.1: Some relevant activities during the installation phase of ProtoDUNE-DP.

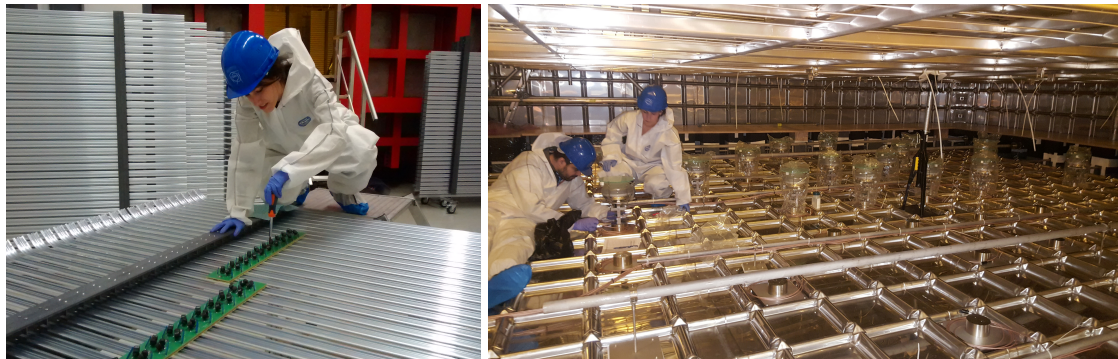


FIGURE 6.2: Pictures taken during one of assembly trials of the field cage (left) and during the PDS installation (right).

The field cage installation was staged thanks to its modular design. Several assembly trials and VHV tests in air were carried out to check the performance, with satisfactory results (see picture in Figure 6.2 left). However, the VHV extender was not tested in a standalone mode before its installation in the detector due to time constraints. Given the critical role of the extender, it is considered now that a careful characterization of the component behaviour would have been fundamental to ensure its integrity and good operation.

A crucial activity at this stage was the CRP individual testing at the nominal HV in realistic cryogenic conditions and in reasonably pure GAr. The goal was to check the electrical and mechanical performances of the system. The setup, known as cold box (see

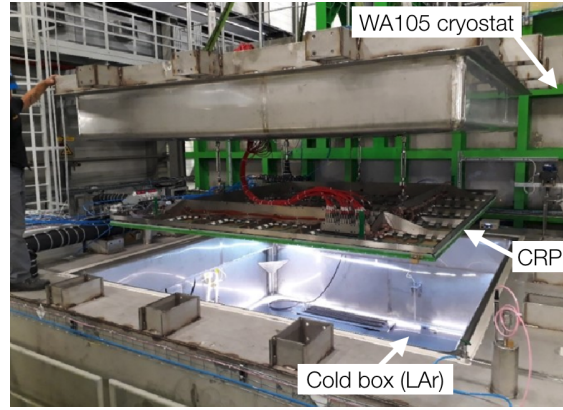


FIGURE 6.3: Cold box setup for the CRP testing.

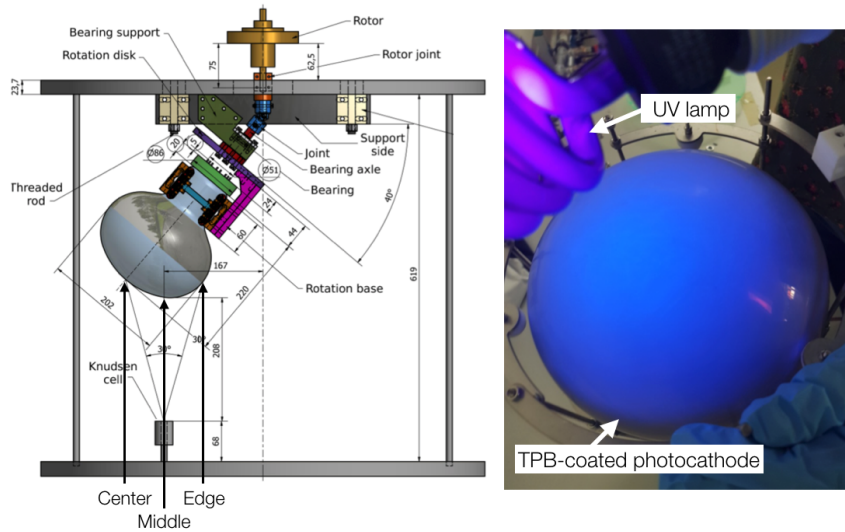


FIGURE 6.4: Left: Schematic design of the evaporation system [147]. Right: Picture of one PMT photocathode illuminated with a UV lamp after the TPB coating.

Figure 6.3), had inner dimensions of $1 \times 3.9 \times 3.9 \text{ m}^3$ and passive thermal insulation. This large box was filled with LAr, and the cryogenic system and safety infrastructures of the WA105 detector were exploited. New LAr was added to compensate the evaporation loss so the LAr level was kept constant. Interesting results for the later CRP operation in the detector were obtained from these tests [164]. The level meters were tested in the cold box together with the CRPs and the cryogenic cameras.

Concerning the PDS and the LCS, the installation at NP02 was smooth and took approximately one week [137] (see picture in Figure 6.2 right). Before being installed on the cryostat membrane, the gain and dark current of each PMT were measured in air to assure the PMTs did not suffer any damage or significant behaviour change during the transport and storage at CERN. As planned, the more fragile components (optical fibers) were installed last to minimize the risk of them suffering any damage. Several tests to ensure a proper performance of the fibers and cables were performed during the installation. The PMT orientation and the calibration fiber position were set as explained

in Section 4.9.1.2 for an optimal collection of the light. The components of both the PDS and the LCS had been carefully characterized at RT and CT [118, 151], as reported in Chapter 5.

The 36 installed PMTs had TPB coating on the photocathode (evaporated after the characterization). The coating procedure was performed at CERN in summer 2018 and required one month. The CERN Thin Film Facility developed for the ICARUS experiment was used [147]. In the setup (Figure 6.4 left), the PMT position is optimized for an uniform coating. All PMTs were coated with more than 0.2 mg/cm^2 in the middle. The maximum difference in thickness is less than 20% from the edge to the middle (middle-center $<5\%$). Different tests and checks were performed to ensure the successful TPB deposition (Figure 6.4 right).

In June 2019, it was decided to change the WLS of 30 PMTs from evaporated TPB to a PEN sheet on top of each PMT. The reason for this conservative approach was explained in Chapter 4: the solid PEN film is a safer option than the deposited TPB dust which is susceptible of dissolving in LAr. The WLS replacement took place in situ: TPB was fully removed and PEN foils were installed instead.

6.2.2 Purging and filling

The main steps after the cryostat closure are summarized in Table 6.2. First, purified GAr was injected at a rate of 50 g/s inside the cryostat from the pipes on the floor in order to remove the air. The re-circulation circuits for gas and liquid were also purged with GAr. When $\mathcal{O}(\text{ppm})$ nitrogen and oxygen levels were achieved (small risk of ice formation), an array of nozzles sprayed droplets of LAr from the top. Also, a small volume of LAr was injected at the bottom of the cryostat. At this point, the argon excess that could not be re-condensed was released in the atmosphere. About 750 t of LAr were then transferred into the NP02 cryostat ($\sim 40 \text{ t}$ per weekday) from an external cryogenic storage tank after passing through purification filters. The detector was filled through pipes near the floor, from bottom to top. The last step was the LAr purification through the *piston method*, using the re-circulation pump and filtering system, and requiring several filter unclogging interventions. Since then, the liquid purification was always active and high LAr purity levels were kept with drift electron lifetime larger than 9 ms [164].

14 th Jun - 1 st Jul 2019	GAr purging
1 st -5 th Jul 2019	Cooling using LAr sprayers
5 th Jul 2019 - 9 th Aug 2019	LAr filling
9 th Aug 2019	LAr purification starts

TABLE 6.2: Purging, filling and purification phases in ProtoDUNE-DP.

6.2.3 Commissioning phase

The commissioning of the detector began on the 10th of August 2019, right after the LAr filling was completed. Some activities during this phase were the calibration of the level meters, the control of the CRP alignment and the testing of the extraction grid HV. The measured CRP planarity pointed to a shape distortion mostly localized on the two opposite corners (saddle-line deformation). In addition, the extraction grids of the four CRPs presented HV trips at about 3 kV that were mitigated by protecting the SHV cables and connectors. The PDS and the LCS were also commissioned. Upgrades on the light DAQ software were developed in parallel to the first PMT runs. A fine tuning of the SPE-level illumination with the LEDs and the optimization of the acquisition parameters were carried out.

6.2.3.1 Bubbling issue

Some bubbling activity was observed right after the detector filling. The bubbling emerged around two points:

- **The VHV feedthrough emitting heat:** here the bubbles did not cause an impact on the CRP operation because the source was not close to the active volume.
- **The topmost FC profile (FFS) with accumulated GAr trapped inside** (of unknown origin): the bubbling was concentrated at the joints between neighboring profiles at about 10 cm from below the LAr surface.

The phenomenon was detected thanks to the monitoring with the cryogenic cameras (Figure 6.5 left). Due to the bubbling, a stable operation of the CRPs was initially not possible due to the risk of grid discharges (sparks caused by the exposure to gas) and HV instabilities.

The strategy to temporary mitigate the bubbles was to perform high pressure cycles. Every morning, the pressure inside the cryostat was increased by 35 mbar (from the nominal 1010 mbar value up to 1045 mbar). Thanks to this procedure, the average temperature increases rather than evaporating the LAr at the surface. When there is no longer a thermal equilibrium, the bubbling disappears (Figure 6.5 right), allowing a stable

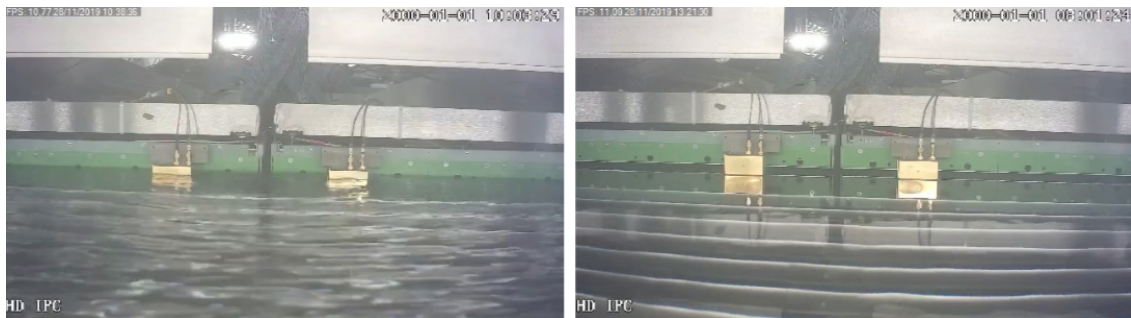


FIGURE 6.5: Pictures taken with the cryogenic camera system. Left: Bubbles from the FC perturbing the LAr surface. Right: No bubbling during a high pressure cycle.

operation and data taking (August - September 2019). In the evening, the pressure was set back to the nominal value to deal with the LAr expansion.

In October 2019, further investigation on the bubbling issue demonstrated that pressure increments of about 10 mbar for 2-3 h allowed the bubbling quenching for a period of about one week. Thus, pressure bumps were performed systematically ever since for a stable operation. Every Monday morning since the end of November 2019, a two-hour pressure bump was scheduled. The nominal pressure was changed to 1045 mbar, which is also closer to the expected pressure in DUNE.

6.2.3.2 VHV commissioning

At least five stability floors (HV steps) were foreseen before reaching the nominal HV on the cathode (-300 kV). The ramp-up started right after the LAr filling completion. First, a HV of -60 kV was set and during two days a stable behaviour was observed. Then, a HV of -200 kV was applied (increasing in steps of 50 kV with 15-30 min of plateau). No problems were found. However, a further increase up to -250 kV caused a current trip ($>500 \mu\text{A}$) after 10-15 min. The later attempts to raise the HV were not successful since current spikes were always observed.

A series of tests and simulations confirmed that there was a problem in the HV extender with a short circuit between the inner conductor and the topmost outer ring (at about 1/4 of the drift). As explained before, the HV extender was not tested in a standalone mode before being installed, so its behaviour at voltages above 100 kV was not predictable. According to the manufacturer, a defect in the construction of the G10 insulator could be the cause of the failure.

The cathode HV was most of the time at 50 kV (LEMs tested up to 3.6 kV across) before the VHV repair. The electric field in the active volume was calculated with a finite element method (FEM) model, considering -50 kV at the cathode and including the space charge effects [164]. According to the results, the field in the operation conditions (with the short circuit) is fairly uniform in the top part of the drift (along 1-1.5 m) and away from the FC walls: 0.15-0.20 kV/cm, 30-40% of the target field of 0.5 kV/cm at -300 kV. Field maps obtained from a COMSOL simulation will be presented in Chapter 8 (see Figure 8.13) as they are used in the light data analysis.

6.2.4 Operation and data taking

The initial plan of ProtoDUNE-DP included the operation of the detector along with the H2-VLE (Very Low Energy) beam line of the LHC for several months in 2018 before the second long shutdown (LS2) which began at the start of 2019. Unfortunately, the detector installation had several delays and the data taking with the beam was not possible. Nevertheless, the detector was operated with cosmic rays from mid-June 2019 to mid-September 2020 (15 months).

27 th Jun 2019	First scintillation signal detection
29 th Aug 2019	First cosmic ray tracks recorded in the anode
Nov 2019	CRT system installation
15 th -17 th Jun 2020	VHV intervention
22 nd Jul 2020	Re-filling with NP04 liquid
14 th Aug 2020	First N ₂ injection
28 th Aug 2020	Second N ₂ injection
4 th Sep 2020	Detector operation ends
7 th Sep 2020	Cryostat emptying begins

TABLE 6.3: Some activities and milestones during the operation of ProtoDUNE-DP.

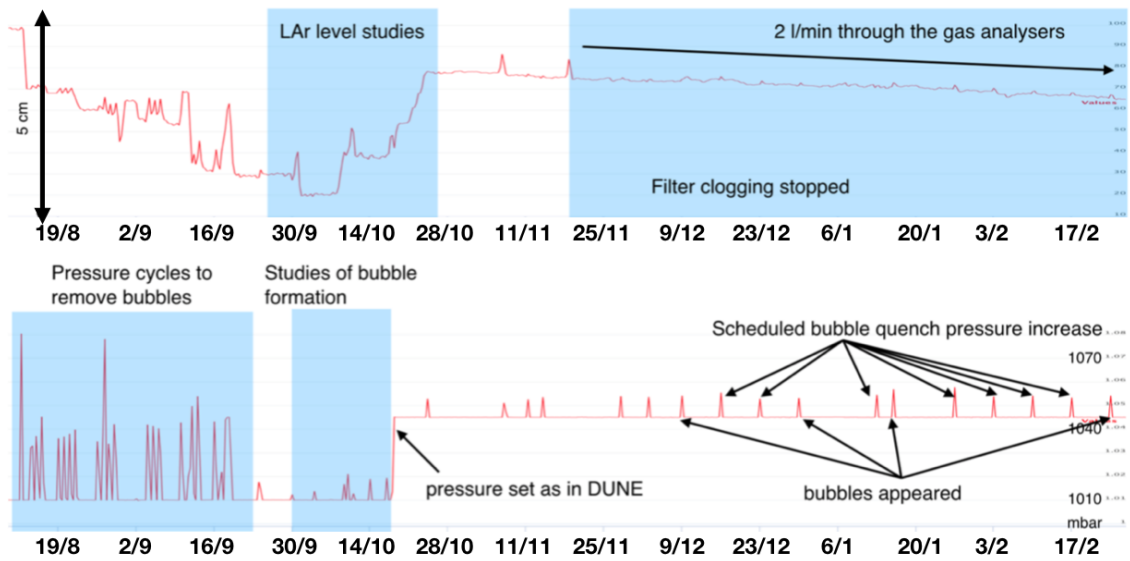


FIGURE 6.6: Summary of the cryogenic performance of ProtoDUNE-DP from August 2019 to March 2020. Top: LAr level. Bottom: Pressure.

A summary of the highlights during the operation phase is given in Table 6.3. The analog and digital electronics, the White Rabbit timing system, and the DAQ back-end system demonstrated an excellent performance during all the detector operation. The cameras (power supplies and heaters) induce significant noise levels on the electronics, so they had to be switched off during the data taking. The cryogenic operation of the detector during eight months (August 2019 - March 2020) is illustrated in Figure 6.6. The increase of the nominal pressure can be observed as well as the pressure bump cycles. Regarding the LAr level, no significant changes were detected since October 2019.

In view of the VHV problem found during the commissioning, a plan to remotely repair the extender was developed. The cryostat was partially emptied by evaporation (about 150 t of LAr, 2.5 m height) for the intervention. After the VHV surgery in June 2020, the liquid volume was filled back to the nominal level by transferring liquid (about 230 t) from the ProtoDUNE-SP cryostat (NP04), and the liquid purification was resumed. Five operation stages can be distinguished in terms of the LAr status (see Table 6.4). After

Time period	Liquid status
10 th Aug 2019 - 4 th May 2020	LAr nominal level
4 th May 2020 - 22 nd Jul 2020	LAr evaporating
24 th Jul 2020 - 14 th Aug 2020	LAr + LAr + Xe(~ 1.7 ppm) + N ₂ (~ 1.5 ppm)
14 th Aug 2020 - 28 th Aug 2020	LAr + Xe(~ 1.7 ppm) + N ₂ (~ 2.5 ppm)
28 th Aug 2020 - 4 th Sep 2020	LAr + Xe(~ 1.7 ppm) + N ₂ (~ 4.5 ppm)

TABLE 6.4: Liquid conditions during the operation of ProtoDUNE-DP. More details can be found in [137].

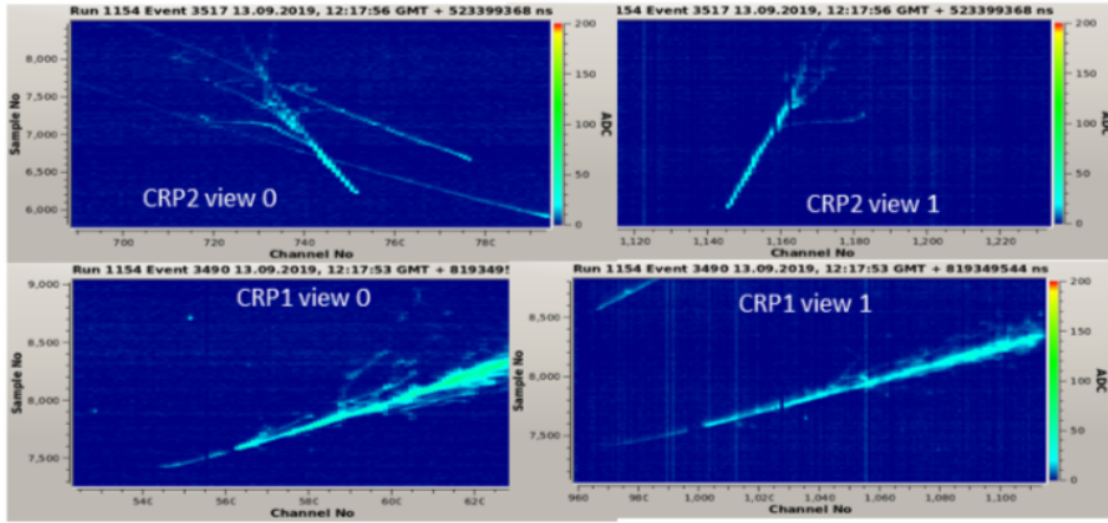


FIGURE 6.7: Gallery of tracks (raw data display). Conditions: LEMs at 2.9 kV, grids at 6.0 kV and cathode at -50 kV. No noise filtering, 400 μ s electron lifetime and random trigger mode.

the re-filling, the liquid was composed of LAr, xenon (Xe) and nitrogen (N₂), in different concentrations. The goals of the nitrogen injections were to evaluate the quenching effect on the sparking and the CRP stability, and study the light attenuation.

Various activities during the operation were focused on the study of the CRP performance. In particular, studies on the CRP gain as a function of the LEM HV, and its stability in correlation with the LEM charging up effects were developed in different data taking campaigns. Moreover, the automatic HV recovery of the system after spark events was optimized. Figure 6.7 shows some examples of tracks recorded with the charge readout system. In 2020, the long term stability of the CRP system was investigated in different configurations. The 72 LEMs of the two instrumented CRPs (36 per CRP) were operated for more than 2700 h (mid-August 2019 - mid-March 2020). An average effective gain around 2 was achieved at the LEMs but the sparks caused inhomogeneities in the charge deposition. At the time of this writing, the analysis of the CRP system performance is still ongoing and a technical publication on the topic is in preparation.

6.2.4.1 VHV extender intervention

An intervention to fix the VHV extender issue took place in summer 2020. The plan was to repair the shorted connection for a deeper and more uniform electric field. The LAr level was lowered to expose the HV links to be cut. In order to achieve that, the argon condensation and the re-circulation pumping were stopped to allow the LAr to evaporate. The VHV surgery was performed on the 17th of June 2020, remotely, using tools mounted on a 3-m long bar. Scissors and hooks were needed to cut the faulty HV links and recover them. The cryostat was opened to air for 4 h and the purification was re-started on the 19th of June 2020. On the 15th of July 2020, a second intervention was carried out to replace the VHV feedthrough by an identical one. The cryostat was re-filled with liquid from ProtoDUNE-SP (NP04) up to the nominal level, and the detector operation was resumed on the 5th of August 2020 after one week of VHV commissioning tests.

The short between the inner conductor of the extender and the FC was solved thanks to the intervention. However, the first tests of the VHV system showed that beyond -50 kV, the higher the cathode HV, the higher the rate of current spikes. This was caused by a current component flowing from the VHV extender surface to the FC connection due to an open circuit.

The analysis of the PMT data taken during the VHV tests (cathode ramping up) was useful to monitor the discharges produced in the extender. In particular, the rate of small signals (SPE-like pulses) was studied and it was observed that the PMT under the extender (FA0137, TPB) detected almost the double of the rate seen by the other (TPB) PMTs, and such a rate increased with the cathode HV. In general, the results from the light measurements point at a significant spark production (light) around the extender causing fatigue (see Section 5.2.2.3) in the PMT response. An example of detection pattern can be

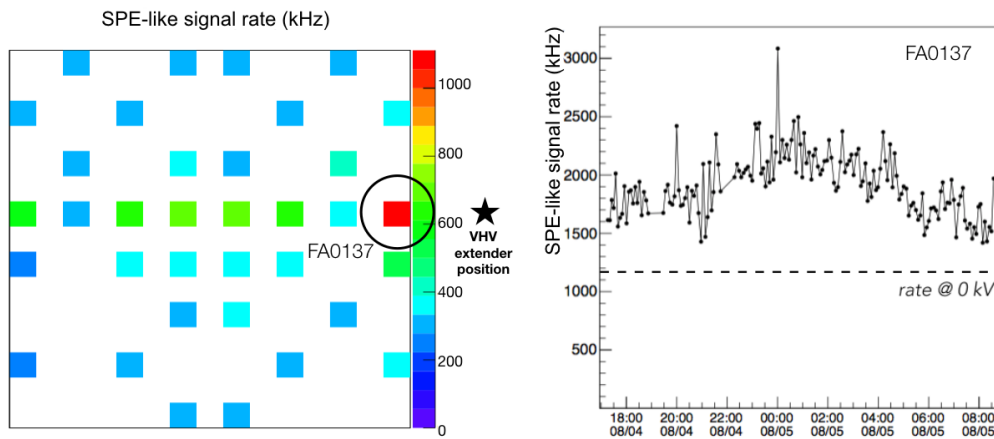


FIGURE 6.8: PDS results during the VHV tests (after the extender intervention and re-filling with LAr+Xe+N₂). Left: Rate of small pulses ($\sim$ SPE) in PMT waveforms (random-trigger), with cathode at -120 kV and PMTs at 10^7 gain. Top view of the detector, where the layout represents the PMT array in the detector. The positions of the VHV extender and the PMT underneath are indicated. Right: Evolution of the rate of small pulses ($\sim$ SPE) in the waveforms (CRT-trigger) of the PMT under the extender (FA0137) operating at a $5 \cdot 10^6$ gain, with cathode at -120 kV.

seen in Figure 6.8 left, while the plot in Figure 6.8 right shows the rate fluctuations with time monitored with the PDS (similar to the measured current fluctuations).

In conclusion, a regular operation of the VHV system in nominal conditions was not achieved despite the repair intervention. The electric field obtained was still not uniform, and important spikes and fluctuations of the current around the VHV extender prevented operating at the nominal field.

6.3 PDS performance

All the PDS components were operational since the beginning of the data taking, which started on the 27th of June 2019 in GAR. The LAr level reached the top of the PMT photocathodes on the 8th of July 2019 (Figure 6.9). The detection of VUV light from LAr scintillation by the 36 PMTs demonstrates the good performance of the two WLS deployed in the PDS: TPB coating and PEN foil. Examples of light signals recorded with one PMT in GAR and LAr can be seen in Figure 6.10. It can be observed that the noise level in the PMT waveforms is very low.



FIGURE 6.9: Picture taken with the cryogenic camera pointing to the PMT array taken on the 8th of July 2019. The LAr level had just completely covered the PMTs.

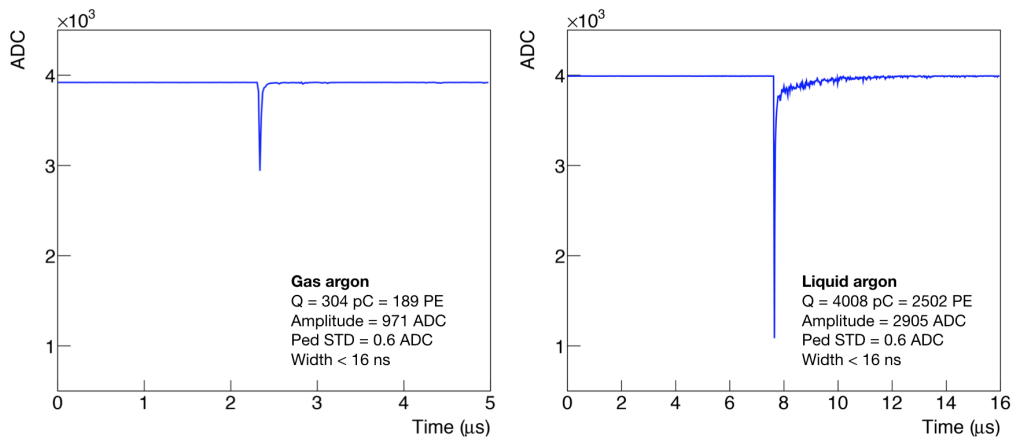


FIGURE 6.10: Examples of scintillation light signals in GAR (left) and LAr (right). Both correspond to a PMT gain of 10^7 and no fields in the detector.

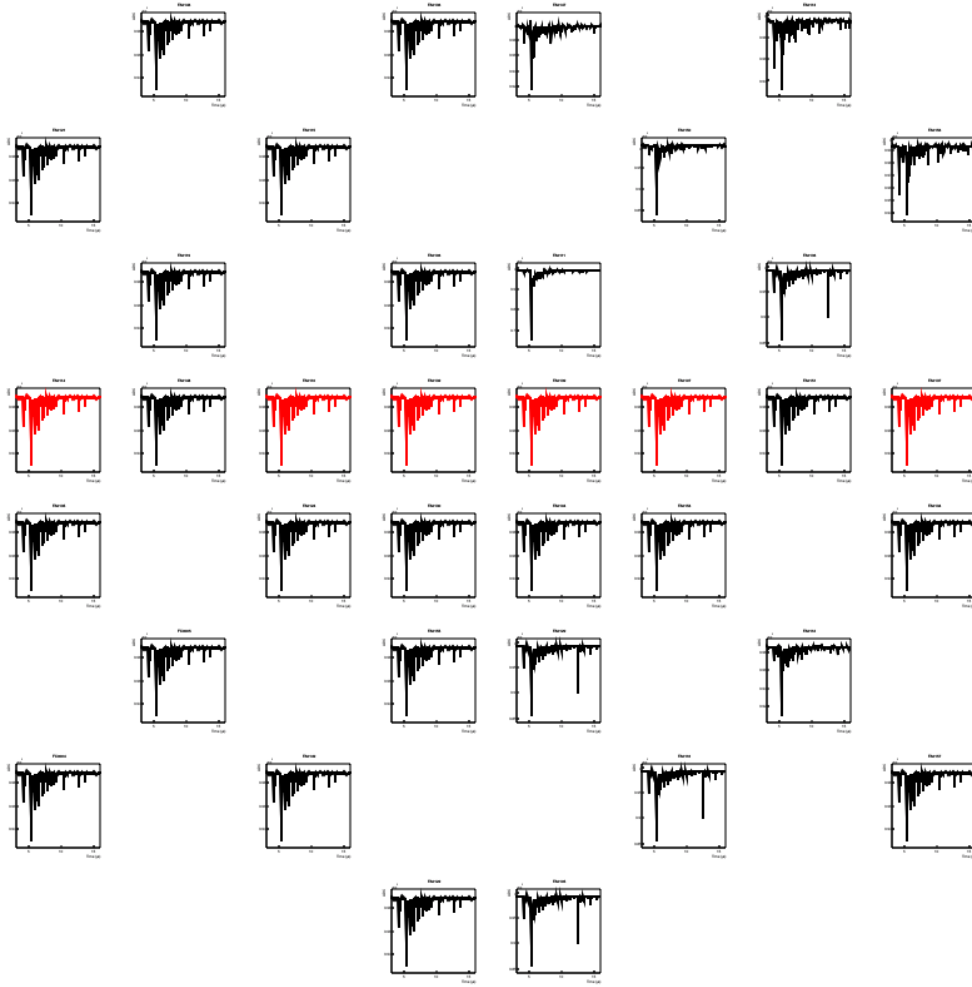


FIGURE 6.11: Example of a scintillation light event detected by the PDS. The waveform layout represents the PMT array in the detector: TPB PMTs in red and PEN PMTs in black. The run was taken with PMTs at 10^7 gain and no fields in the detector.

It must be noted that PMT data taking was possible typically during 1-2 h per day. PMT HVs had to be switched off to allow the operation of the cameras and daily measurements of the purity monitors. These activities implied illuminating the detector with LEDs and lamps that could damage the PMTs if they were turned on. The monitoring with the cameras took place very often at the beginning of the data taking to survey the status of the liquid surface and CRPs. However, since November 2019, longer time periods of PMT operation (up to 12 h) were allowed, typically at night. Thanks to these long runs¹, the stability of the PDS was proven.

Figure 6.11 exhibits a S1 signal detected in coincidence by the 36 PMTs. The primary scintillation signal can be exploited with different purposes [164, 90]. For example, the decay time for the triplet state obtained from the scintillation light profile has been monitored during 15 months: the average result ($\tau_{slow} = 1.46 \pm 0.02 \mu s$ [165]) points out a low contamination level of the LAr during most of the operation time. This monitoring can

¹Along this document, *run* refers to a data set taken in the same day under the same conditions.

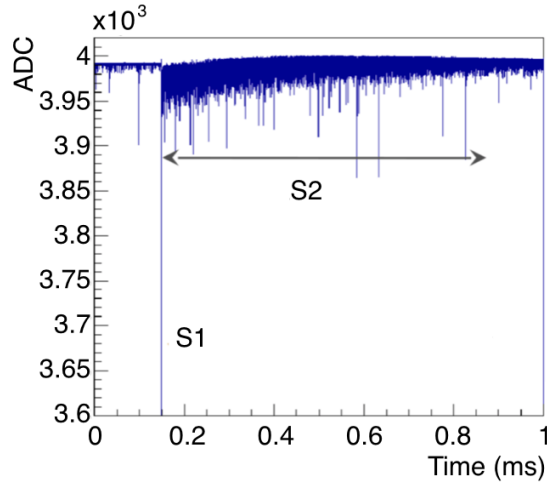


FIGURE 6.12: Example of PMT waveform with S2 signal from the electroluminescence in GAR: the S2 starts as a continuum right after the S1. The field conditions were: cathode at 50 kV; grids at 6.2 kV; and LEMs at 0-8-3.5 kV. A zoom in the y-axis is applied to focus on the S2 signal.

be used to detect important LAr purity changes. Other analyses of interest on the S1 signal will be reported in Chapter 8.

A crucial milestone achieved was the detection of electroluminescence (S2) signals by the 36 PMTs from more than 6 m far away from the PMT array. In the light data runs with fields (drift, extraction and amplification), the S2 signal from the electroluminescence of the electrons extracted in the GAR phase can be observed and valuable information can be extracted (drift time, track topology, etc.). An example of PMT waveform with S2 signal is displayed in Figure 6.12.

6.3.1 Summary of the collected light data in LAr

The PDS took data during all the liquid stages (see Table 6.4): 1) pure LAr at the nominal level (~ 10 months), 2) pure LAr during evaporation (~ 11 weeks), 3) LAr + Xe + N₂ with different concentrations of N₂ (~ 6 weeks), and 4) LAr + Xe + N₂ during the emptying of the cryostat (~ 3 months). The light profile change when adding xenon can be seen in Figure 6.13) [90]. Note that the analyses on ProtoDUNE-DP light data presented in this thesis are based only on PMT data corresponding to the first operation period when the detector only contained pure LAr and the liquid level was relatively constant around the nominal value.

From the trigger point of view, Table 6.5 contains a summary of the light data collected. In total, 130.7M events (675 h) were acquired, being the PMT self-trigger the most-used trigger mode. On the other hand, Table 6.6 presents the run summary according to the different field conditions in the detector (cathode and voltage across LEMs). It can be seen that most of light data (85.1M events, $>65\%$) correspond to operation with no fields.

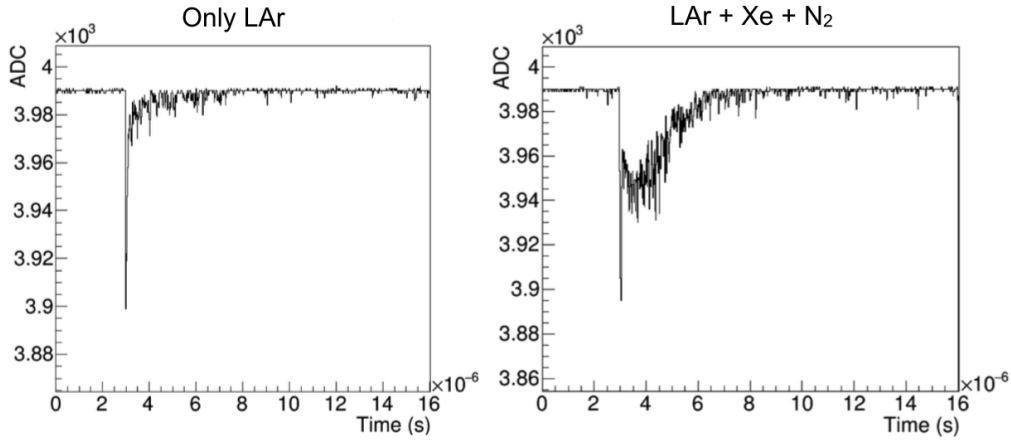


FIGURE 6.13: PMT waveforms with detector full of LAr (left plot) and LAr+Xe+N₂ (right plot). An increase in the light uniformity due to the longer Rayleigh scattering length of Xe is expected as well as light absorption due to the N₂ impurities.

Trigger mode	# of events (M)	Time (h)
PMT	85.3	93
Calibration	30	42
Random	14.7	21
CRT panels	0.6	515
Total	130.7	675

TABLE 6.5: Light data collected in different trigger modes (June 2019 - November 2020).

Drift status	LEM voltage (kV)	# of events (M)	Time (h)
OFF	–	85.1	342
ON	0	13.6	72
	2.5-3.6	7.7	212
Test	–	23.2	48
Total	–	130.7	675

TABLE 6.6: Light data collected in different field conditions (June 2019 - November 2020).

6.3.2 Analysis framework

The light data acquired with the PDS are available in two formats: MIDAS format file (raw data) and ROOT format file (processed data). The former is copied as backup file (in case the root conversion failed) and the latter is a more manageable format used in the data analysis. The ROOT file contains a tree with all the relevant variables of the run: pre-trigger time, PMT HVs, number of events, window size, timestamp from the White Rabbit, ADC values, digitalization sampling, etc.

The light data analysis is developed in ROOT² [167], an object-oriented data analysis framework for data processing, born at CERN, commonly used in high-energy physics. Some general comments on the analyses contained in this thesis are the following:

- The analyzed data were acquired with a sampling of 16 ns and a readout window between 2 μ s and 1 ms.
- In general, the pedestal is computed event by event as the average ADC value of the pre-trigger first 20 samples (320 ns) of the PMT waveform in a row with RMS below 2 ADC counts (stable baseline).
- A PMT gain correction is always applied using the results of the closest calibration.
- Events saturating the ADC range (4096 ADC counts) and/or lying in the non-linear response range of the PMTs (see Section 6.3.4) are excluded from the analysis (except for studies based on an amplitude threshold). The fraction of excluded events over the total depends on the trigger mode, the PMT gain and the particular PMT.
- The main variables associated to a PMT signal that are studied are the maximum amplitude (maximum sampled signal to the baseline), the peak time (when the maximum amplitude peaks), and the integrated charge. The charge in PE units ($Q[\text{PE}]$) in a certain time window (Δt) is obtained as follows:

$$Q[\text{PE}] = \left(\sum_{i \in \Delta t} (Ped_{mean} - Q_i)[\text{ADC}] \times \Delta t[s] \right) \cdot \frac{1}{G \cdot 50 \Omega} \cdot \frac{1 \text{ PE}}{1.602 \cdot 10^{-19} \text{ C}} \cdot \frac{2 \text{ V}}{4096 \text{ ADC}} \quad (6.1)$$

being Ped_{mean} the mean pedestal, Q_i the waveform value in each sample, G the PMT gain, 50Ω the ADC resistance, $1.602 \cdot 10^{-19} \text{ C}$ the absolute electron charge and $(2/4096) \text{ V/ADC}$ the dynamic range.

- The three charge components or integration windows considered (at the usual 16-ns sampling) are:
 - Fast component: Q_{fast} $([-32; +64]\text{ns}, 6 \text{ bins}, 96 \text{ ns})$.
 - Slow component: Q_{slow} $([+64; +3968]\text{ns}, 244 \text{ bins}, 3904 \text{ ns})$.
 - Total charge: $Q_{total} = Q_{fast} + Q_{slow}$ $([-32; +3968]\text{ns}, 250 \text{ bins}, 4 \mu\text{s})$.

where the integration range is opened around the peak time of the signal.

6.3.2.1 PDS-CRT matching

The data files from the CRT system are also available in EOS both in raw and ROOT formats. The CRT files include the relevant parameters of the trigger (see Section 4.7) like coordinates of the fired scintillators (entry and exit of the track), timestamp, time of flight, multiplicity and charge of the fired scintillators and flag of clean coincidence.

A systematic matching of all the CRT runs with the corresponding PDS runs was carried out. This process is done off-line and is based on the agreement between the timestamps recorded by both systems. The CRT timestamp comes from an internal clock (corrected to

²<https://root.cern>

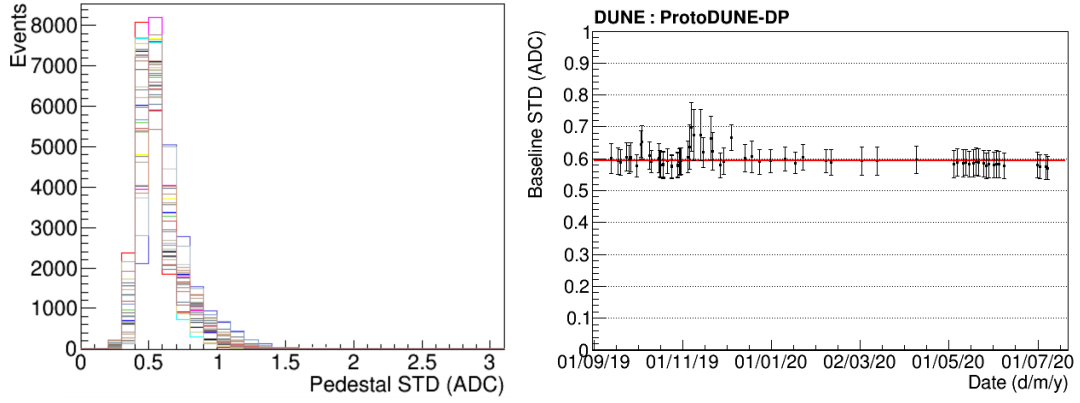


FIGURE 6.14: Pedestal STD at a gain of 10^7 : final average fluctuation values for each PMT (left) and measured baseline STD (average of 36 PMTs) as a function of time (right).

match the White Rabbit timestamp) and has a precision of 1 s whereas the PMT timestamp is taken from the White Rabbit system that provides a 1-ns precision. Therefore, the latest PDS timestamp recorded per event is used to find its CRT peer. Once the unambiguous matching is ready, a new ROOT file with the CRT information per matched event is created to be used in the light data analysis. The events that can not be correctly matched ($<0.1\%$ per run; due to trigger overlaps or desynchronization of the CRT clock) are not included in the final output files.

6.3.3 Signal-to-noise ratio

The signal-to-noise ratio has been studied. The small fluctuation of the baseline in the PMT waveforms is remarkable (Figure 6.14): 0.6 ± 0.1 ADC counts of pedestal STD at a PMT gain of 10^7 , on average, over the detector operation. The SPE amplitude has been also characterized as a function of the PMT gain and the results will be discussed in Section 8.2. In particular, the average SPE amplitude found at a 10^7 gain is 7 ± 2 ADC counts. Hence, a signal-to-noise ratio greater than 11 is achieved with the PMTs operating at that gain.

6.3.4 Study of the PMT response

A basic characterization of the PMT response has been carried out to define the linear dynamic range of each PMT in later analyses. The main aspects under study are the light signal rate and the amplitude-charge correlation. In total, four PMT-trigger runs (with no detector fields, 20k events and $16\text{-}\mu\text{s}$ readout window) are considered. The gains are the same for all PMTs but different in each run: $5 \cdot 10^6$, $1 \cdot 10^7$, $2 \cdot 10^7$ and $5 \cdot 10^7$. These data were taken with a threshold at 3950 ADC (about 50-100 ADC of amplitude) on FA0139 (TPB, ADC channel #21). The relatively-low trigger threshold provides signals of different amplitudes. These studies only intend to give a preliminary idea of the PMT behaviour, useful in the more detailed characterization of the scintillation light signals that will be reported in Section 8.4.2.

6.3.4.1 Dynamic range for a linear PMT response

In order to investigate the dynamic range for which the PMTs exhibit a linear response, the rate of signals detected by the PMTs as a function of their amplitude is studied. First, the signal amplitude per event is obtained and the number of signals with an amplitude larger than a threshold are counted. In that way, a threshold scan is performed off-line in the analysis. Finally, the rate is calculated as the number of signals over the run time according to the timestamps of the first and the last events. It has been verified that, for the triggering PMT (FA0139, ch#21 in Figure 4.8), the results are similar when the threshold scan is done on-line during the data taking. In that case, a run is taken for each amplitude (trigger) threshold and the number of recorded events over the run time provides the signal rate.

The results can be seen in Figure 6.15 for a gain of $5 \cdot 10^7$. Similar results are obtained for the other three PMT gains considered. Looking at the signal rate, it is clear that some PMTs suffer an early saturation. The PMTs represented in black (full-range PMTs in the legend) show a non-zero rate up to the upper limit of the ADC range (4096 ADC $\approx$ 80 PE at $5 \cdot 10^7$) while the PMTs in colors (early-saturating PMTs) exhibit a rate drop before reaching the ADC limit. The detector diagram in the figure indicates the position of the 10 PMTs (9 with PEN and 1 with TPB) that have null rate at amplitudes between 45 PE and 75 PE. The early saturation observed in these PMTs points out that the response of each photosensor is unique and must be individually studied in detail before combining several PMTs in a data analysis.

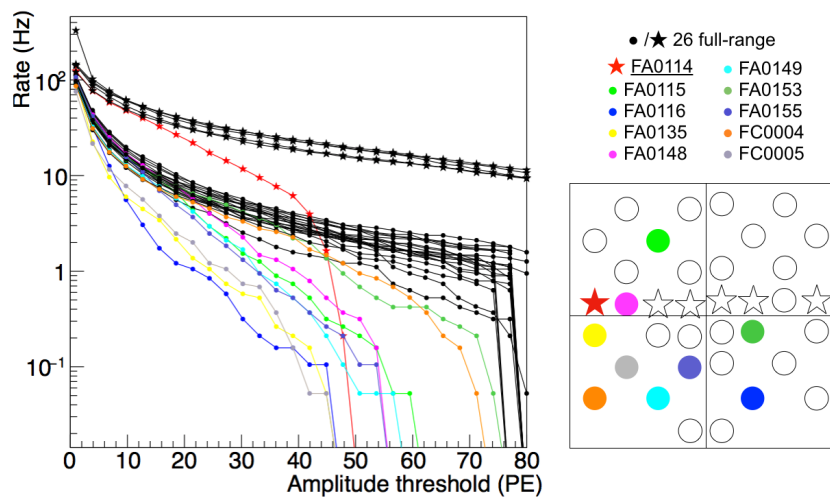


FIGURE 6.15: Rate of signals detected by the PMTs as a function of the amplitude threshold (PE) at a gain of $5 \cdot 10^7$. The channels with signals covering all the ADC range (0-4096 ADC) are in black and the ones with a limited range are in colors. Circles correspond to PEN and stars to TPB PMTs. The diagram on the right side displays the PMT layout in the detector.

6.3.4.2 Amplitude-charge correlation and comet effect

The correlation between the amplitude and the charge is investigated for the charge integration windows defined in Section 6.3.2, namely, Q_{fast} $([-32; +64] \text{ ns}, 96 \text{ ns})$ and Q_{slow} $([+64; +3968] \text{ ns}, 3904 \text{ ns})$. Examples of the fast PMT response (maximum signal amplitude vs. Q_{fast} , both in PE units) are presented in Figure 6.16 for four representative PMTs, including TPB (left panel) and PEN (right), full-range (top) and early-saturating (bottom) PMTs. It can be observed that, at a typical gain of $\sim 1 \cdot 10^7$ (red curves), in full-range PMTs the S1 saturation in amplitude appears for signals with amplitudes beyond ~ 400 PE (for any WLS, as expected). This limit corresponds to the ADC dynamic limit of 4096 ADC counts. Concerning the early-saturating PMTs, the observed behaviour is different and PMT linearity seems to be lost beyond ~ 150 -200 PE in amplitude at $\sim 1 \cdot 10^7$ gain, before reaching the ADC saturation limit. Such a deviation from linearity is expected in all the PMTs for high-charge events but the non-linearities are hidden by the ADC saturation in the case of the full-range PMTs.

From the point of view of the PMT gain, the higher the gain, the lower the amplitude for which saturation starts. For example, if the gain increases by a factor 2 ($\sim 2 \cdot 10^7$), the

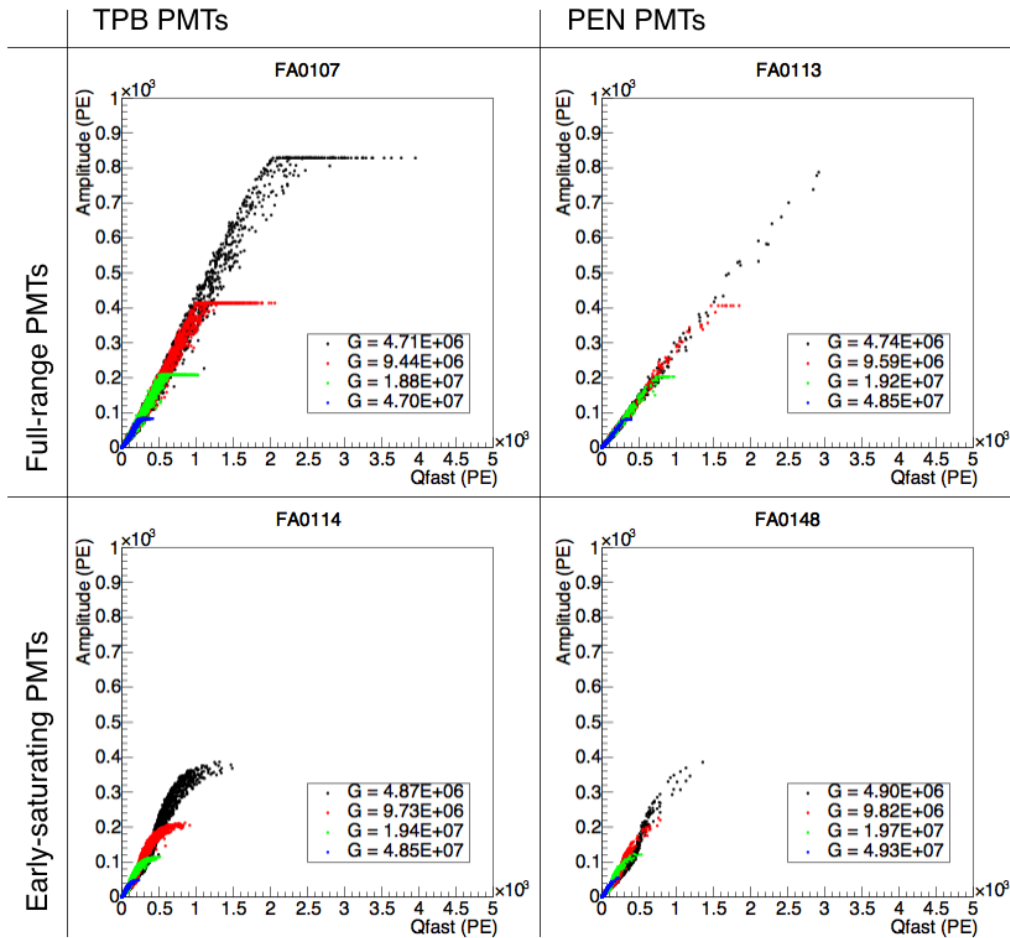


FIGURE 6.16: Amplitude vs. Q_{fast} for different PMT gains and four representative PMTs.

saturation amplitude limit decreases by a factor 1/2 (~ 200 PE), as expected, and the saturation effect is stronger. The observed behaviour is similar to the one already reported in Figure 5.14 right based on the results obtained during the linearity measurements performed at CIEMAT as part of the PMT characterization.

In order to further characterize the response of the PMTs in ProtoDUNE-DP, the so-called *comet effect* that was described for the first time in [86, 85] (with WA105 light data acquired with the same PMT model as in ProtoDUNE-DP) must be taken into account. The comet effect concerns the relation between the fast and slow components of the scintillation light profile: while Q_{fast} keeps increasing, Q_{slow} starts to decrease. This phenomenon can be caused by the high output current induced by the train of pulses arriving to the PMT during a relatively long time period: the end of the dynode chain gets saturated and there is loss of collected charge (leading to a waveform distortion) until the signal ends and the correct signal output is recovered.

The comet effect in ProtoDUNE-DP PMTs is shown in Figure 6.17, where Q_{fast} is plotted as a function of Q_{slow} . The linearity is evidently lost at some same point (depending on the gain) and the sign of the slope of the charge correlation changes. The distortion in the charge distribution is evident at the four PMT gains considered. Two particular PMTs (one TPB and one PEN) are displayed in the figure as examples, but it must be noted that this effect occur in all PMTs, as it can be seen in Figure 6.18 where the Q_{fast} - Q_{slow} correlations for the 36 PMTs at a gain of $\sim 1 \cdot 10^7$ are included. The position of each plot represents the position of one PMT in the detector layout. According to the results, the comet effect is exhibited by all types of PMTs (TPB or PEN, early-saturating or full-range), albeit it is more clear in some PMTs than in others in the charge range under study here.

The 10 early-saturating PMTs identified in the previous sections are located around the left-bottom corner of the PMT array (see the detector top view in the schematic of Figure 6.15). Note that the characterization and installation procedures were the same for all the PMTs. Several hypotheses on the causes of this behaviour have been explored. In particular, the possible influence of the purity monitor activity (including the almost-daily illumination with lamps) has been considered although the PMTs were always off during the purity runs. The three purity monitors are located precisely at the left-bottom corner of the cryostat (top view). Nevertheless, PMT runs taken in November 2020 (about two months after the last purity monitor run) provide similar results to the ones presented: early saturation only in the 10 particular PMTs and linear response up to the ADC limit for the others. Thus, in case the origin of the described differences among PMTs is related to the purity monitor activity, they would have caused a long-term or permanent effect on the PMTs.

In conclusion, although the 36 PMTs are expected to present both saturation and comet effect at certain operating conditions, it is not completely understood why almost 1/3 of the PMTs, relatively grouped in space in the detector, present these effects for signals with smaller amplitude or in the same conditions in which others do not. As a result, the individual behaviour of each PMT must be carefully evaluated in the data analysis given

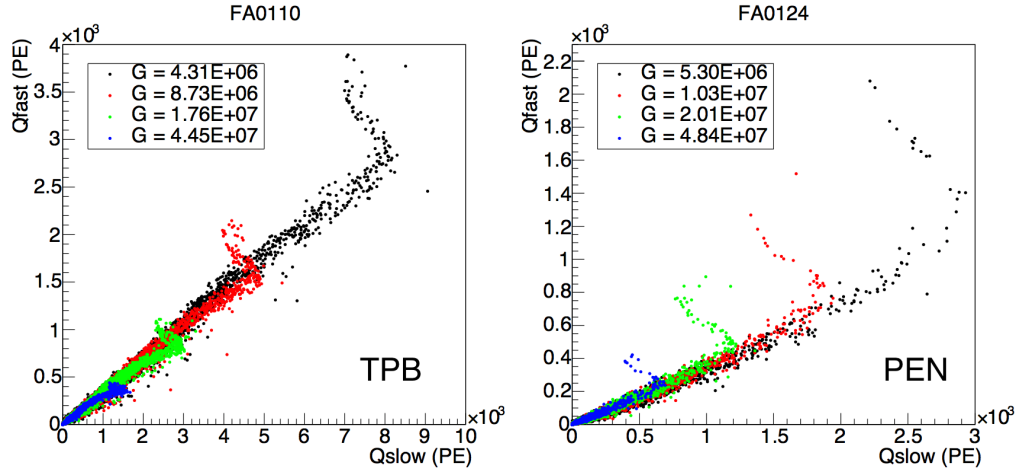


FIGURE 6.17: Q_{fast} vs. Q_{slow} correlations at different PMT gains.

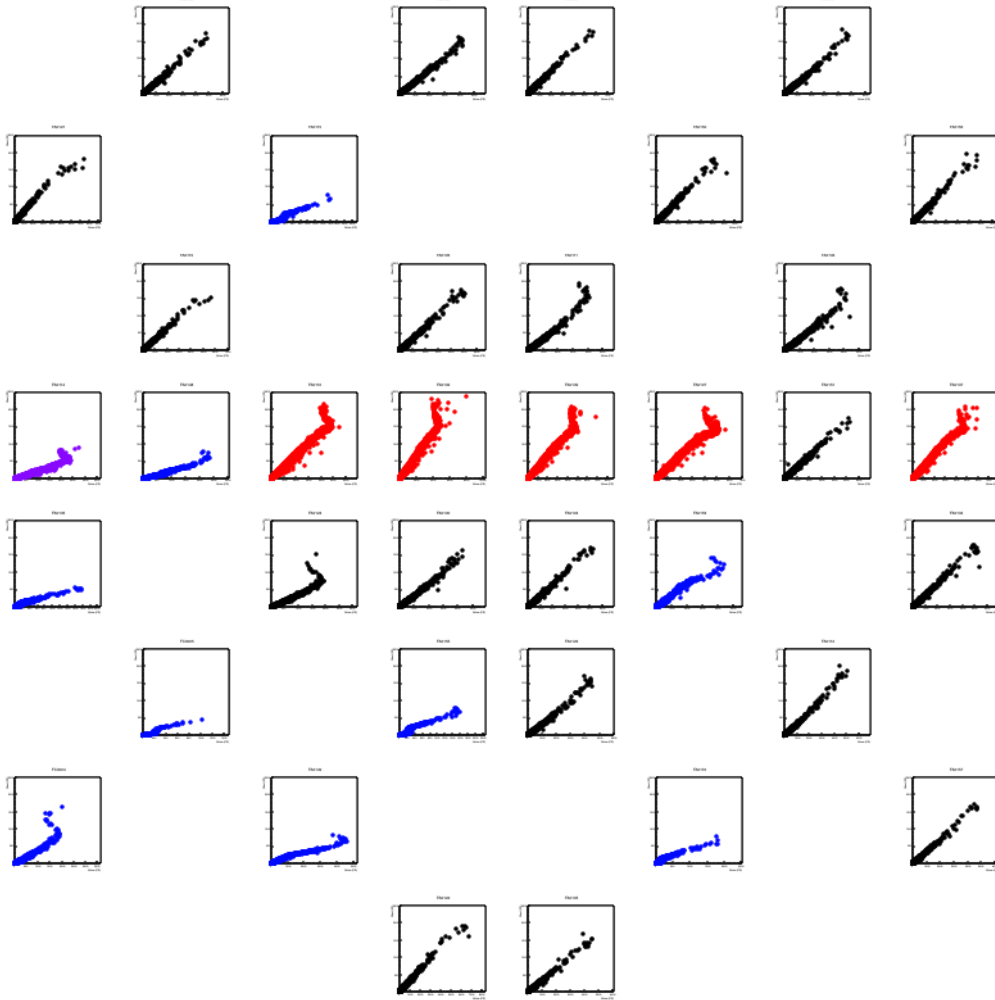


FIGURE 6.18: Q_{fast} (PE) vs. Q_{slow} (PE) for the 36 PMTs ($1 \cdot 10^7$ gain). The vertical scale is the same (0-2500 PE) in all the plots while the horizontal scale is different (up to a few thousands of PE) so the shape of all the distributions can be observed. Each plot corresponds to one PMT and they are displayed according to their positions in the detector. Color legend: red = full-range TPB PMTs; purple = early-saturating TPB PMT; black = full-range PEN PMTs; blue = early-saturating PEN PMTs.

the very different performances that are observed among the 36 PMTs for the same light events.

6.4 LCS performance

In total, over 1200 calibration runs were taken with the LCS of ProtoDUNE-DP (30M events, 42 h) from June 2019 to September 2020. The calibration data taking is done with the custom DAQ software in calibration mode so the light source provides the trigger. The shifter can select the settings for the PMT HV, front-end (sampling, acquisition window size, pre-trigger and ADC channels to acquire), and light source (LED voltage and frequency, number of events, and reference sensor voltage).

There are two calibration approaches: the construction of the complete gain-voltage curve or the measurement of the gain at the operating HV. Both options are considered in the calibration DAQ.

6.4.1 Gain-voltages curves

Complete calibrations (gain vs. HV) are carried out weekly. In the standard configuration, the PMT gain is measured doing a HV scan from 1400 V to 1750 V in 50 V steps. The LEDs are operated all at once at 6.7 V (SPE level) and 1 kHz. The acquisition window is 2 μ s (long enough for a good pedestal estimation), the sampling is 16 ns and the pre-trigger is 50% (pulse at the center of the waveform). At each HV, 20k events are recorded (160k events per calibration). The configuration also includes a waiting time of 3 min between runs to allow the PMT response to stabilize after each HV increase.

6.4.1.1 Calibration analysis: gain determination and errors

A set of programs in ROOT has been developed for the systematic analysis of the PMT calibration runs taken with the LCS. It has turned out to be a fundamental tool to obtain reliable calibration results in a reasonable time (less than 1 h per calibration) and, hence, to enable an updated calibration database to consult. Of the order of 70 complete calibrations (around 560 runs) have been successfully analyzed using this dedicated framework and the codes have been improved in parallel to the data taking.

The gain calibration analysis is staged so partial control outputs can be checked before the process is complete, allowing the early-detection of possible problems associated to the run conditions. In addition, the calibration is organized in terms of the PMT groups illuminated by the same LED (see Figure 4.8). Thanks to this approach, the time analysis gets reduced if not all the LEDs are turned on at the same time. The program can be easily customized and adapted to different configurations like the calibration with the top fibers.

Figure 6.19 shows a calibration pulse (top-left), a fitted SPE spectrum (top-right) and the gain-voltage curves of three PMTs (bottom), all of them obtained with the LCS. Each plot illustrates one step in the algorithm for the gain determination:

- **STEP 1: waveform integration.** The ADC signal of the calibration pulses is integrated to construct the SPE spectrum. First, the mean time position of the SPE peak (maximum amplitude) for each run and PMT is determined processing all the events. This is necessary because the LCS trigger position has been found to oscillate up to 96 ns (6 samples) with respect to the expected time. Then, the waveform in 144 ns (9 samples) around the SPE mean position is integrated to obtain the SPE charge. The pedestal appears centered at 0 because the baseline is subtracted when doing the pulse integration. In this case, the mean baseline is obtained from the first 480 ns (30 samples) of the waveform and the 12% most noisy events (with the highest baseline RMS) are not included in the SPE spectrum.
- **STEP 2: fit of the SPE spectrum.** The SPE charge distribution for a run is fitted with two Gaussian functions: one modeling the pedestal peak (around 0) and another the SPE peak. The difference between the mean of the two Gaussians provides the PMT gain (see Section 5.2.2.2).
- **STEP 3: fit of the gain-voltage curve.** The gain obtained in the previous step is plotted as a function of the PMT HV. Next, a fit is done following the power law $G = AV^B$, being A and B constants dependent on the number, structure, and

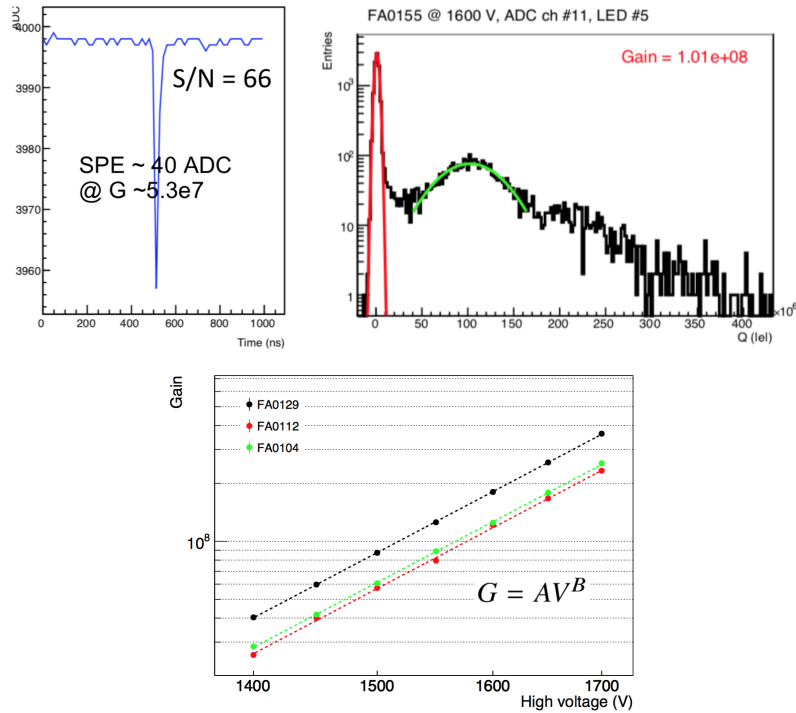


FIGURE 6.19: LCS performance. Top-left: Calibration pulse (SPE) in the PMT waveform. Top-right: SPE spectrum for one PMT fitted to two Gaussian functions. Bottom: Gain as a function of the HV for three PMTs (fitted to a power law).

material of the dynodes [139]. Only the gain values that can be well estimated (good SPE spectrum fit and no ADC saturation) are included in the curves: typically, gain between 10^7 and $3 \cdot 10^9$.

The error is estimated from the difference between pairs of calibrations taken on the same day without biasing down the PMTs: the variation found at 1500 V is 3% while at a gain of 10^7 is slightly larger due to the data extrapolation: 4%. These relative errors are included in all the results shown in the following.

6.4.1.2 Gain stability with time

The collection of complete calibrations taken during the detector operation allows to investigate the PMT gain stability with time. In particular, the gain evolution at 1500 V is studied along 58 calibrations: $\sim 2k$ gain-voltage curves from 464 runs taken during one year. The calibration results are used to calculate the gain at 1500 V for the 36 PMTs ($4 \cdot 10^6$ - $4 \cdot 10^8$ gains).

Figure 6.20 presents the gain evolution of all the PMTs (separated in four groups) during one year of regular operation of the LCS. It has to be taken into account that the PMTs are switched on and off every day (sometimes several times on the same day). Despite this fact, the overall gain behaviour is quite stable with time.

Some comments on the gain stability results are the following:

- A few runs are ignored for some PMTs due to a bad fit of the SPE spectrum (typically in FA0111, FA0124, FA0135 and FC0005).
- Four PMTs (FA0106, FA0119, FA0147 and FA0156) were connected to an oscilloscope for the monitoring of sparks produced in other detector systems: from 16/09/19 to 26/11/19, and from 02/12/19 to 22/12/19. Therefore, no data were recorded from them during those time periods.
- There was a gain drop for a few weeks in two PMTs: FA0111 (29/11/19 - 17/1/20 and 15/6/20 - 27/7/20) and FC0005 (20/7/20 - end of the operation).
- There was a general gain drop at the end of August 2020 after taking data in coincidence with the charge. The cathode reached up to 120 kV and a significant amount of sparks was produced during the runs (see Section 6.2.4.1) that affected the later operation of the PMTs.
- The STD of the gain at 1500 V for all the runs was calculated for each PMT. Figure 6.21 shows the gain fluctuations with respect to the average gain per PMT. On average, the gain STD at 1500 V during one year for the 36 PMTs is $9 \pm 3\%$.

The LCS is essential for a PDS operation in controlled gain conditions. The PMT HV settings for the data taking were given by three reference calibrations performed on 12/09/2019, 26/11/2019 and 28/02/2020. These calibrations were carried out without fields in the detector. The change from one reference to another was done to have updated values, not because any PMT had a significant gain change. Comparing the three reference calibrations, the STD of the gain at 1500 V for each PMT is calculated and then the average

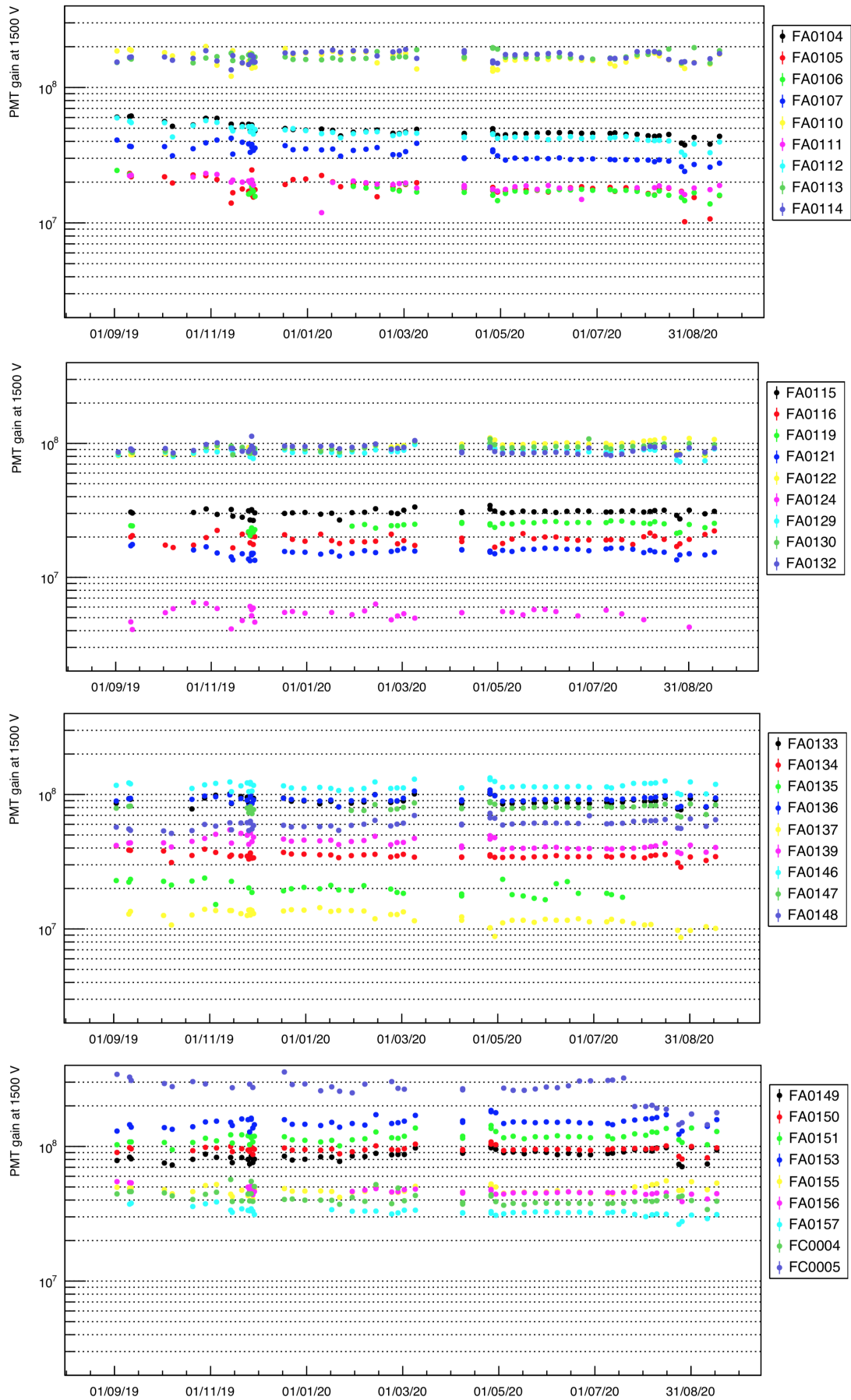


FIGURE 6.20: Gain stability with time at 1500 V for the 36 PMTs of ProtoDUNE-DP during one year of data taking with the LCS.

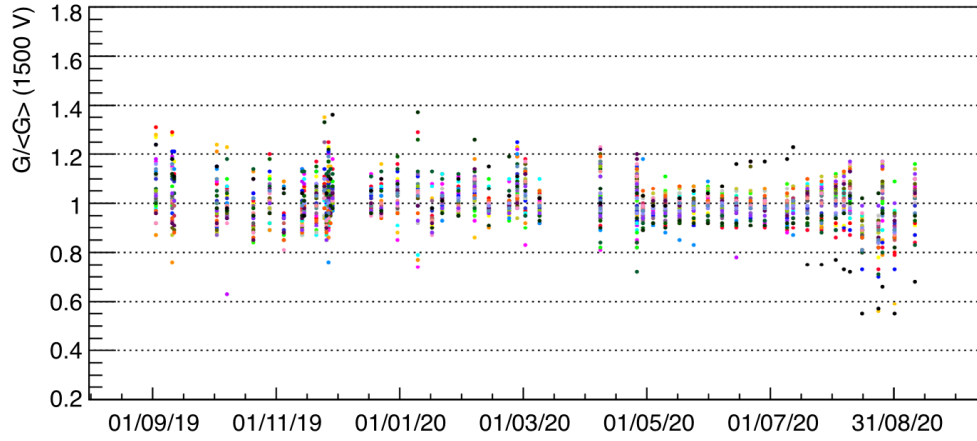


FIGURE 6.21: Gain stability with time for the 36 PMTs at 1500 V with respect to the average gain.

for the 36 PMTs is computed. The result is $7 \pm 4\%$, which is within the average gain variation over a year given before.

6.4.2 CIEMAT vs. CERN calibration results

The gain of each PMT unit was carefully characterized at CIEMAT laboratory before the PMTs were sent to CERN. Three data sets can be distinguished:

- Set A: measurements at RT (2017-2018), reported in Section 5.2.
- Set B: measurements at CT in LN_2 (2017-2018), reported in Section 5.2.
- Set C: measurements at RT before the shipping (June 2018).

On the other hand, the following data sets at CERN are considered for comparison:

- Set D: data at RT (February 2019, right before the PMT installation).
- Set E: average of calibrations during ProtoDUNE-DP operation at CT in LAr (September 2019 - March 2020), reported in Section 6.4.1.2.

Note that the setups were different at CIEMAT and CERN. Namely, the cryogenic conditions were not exactly the same: measurements were done in LN_2 (77 K) at CIEMAT and in LAr (87 K) at ProtoDUNE-DP. All the comparisons presented in this section are made at 1500 V.

Figure 6.22 top-left compares the RT results at CIEMAT: set A vs. set C. The correlation obtained is fairly good and the average gain discrepancy at 1500 V is $20 \pm 39\%$. On the other hand, Figure 6.22 top-right shows the correlation between measurements at RT: set A (CIEMAT) vs. set D (CERN). A Good agreement is observed, with an average gain difference of $34 \pm 26\%$. Finally, Figure 6.22 bottom includes a comparison at CT: set B (CIEMAT) vs. set E (CERN). The average gain variation is $65 \pm 80\%$. The large dispersion among PMTs is clear in the plot and the results indicate that, in general, PMT gains have increased with respect to the PMT characterization at CIEMAT. It is known that the higher operating temperature at ProtoDUNE-DP plays a role in this gain increase. In addition, the

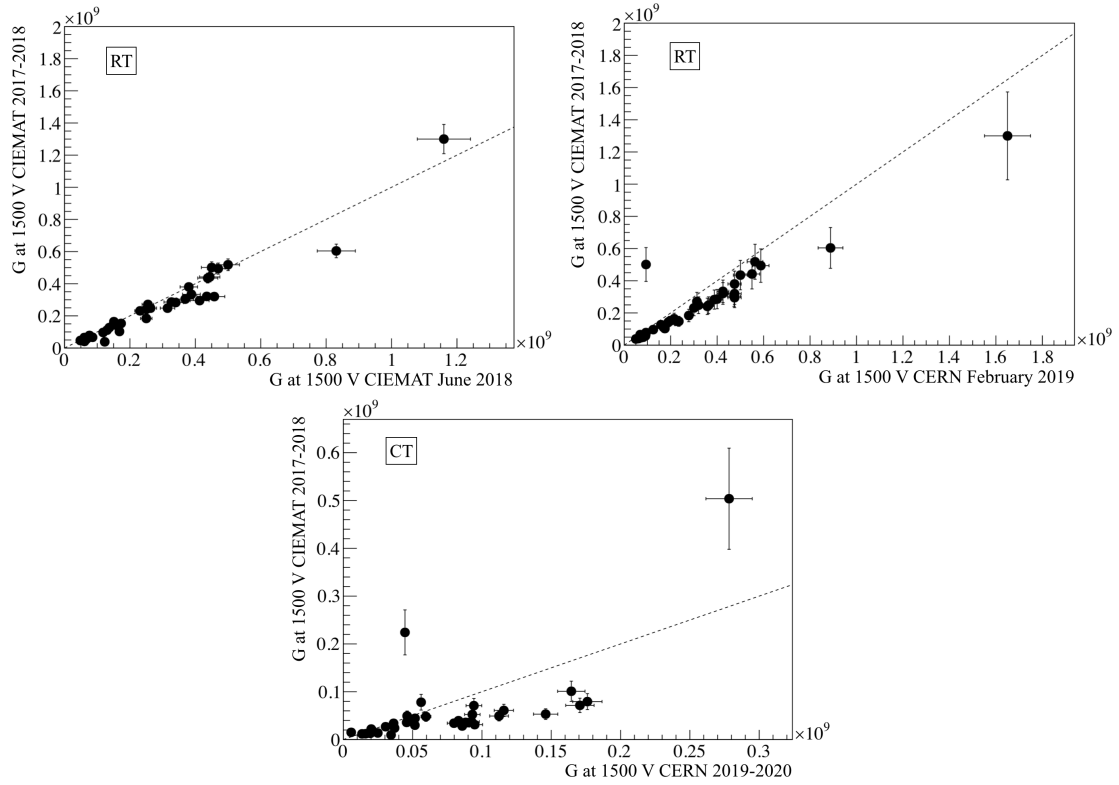


FIGURE 6.22: Comparison of gains at 1500 V. The dashed line corresponds to the identity line (1:1). Top-left: set A (RT, CIEMAT, 2017-2018) vs. set C (RT, CIEMAT, Jun 2018). Top-right: set A (RT, CIEMAT, 2017-2018) vs. set D (RT, CERN, Feb 2019). Bottom: set B (CT, CIEMAT, 2017-2018) vs. set E (CT, CERN, Sep 2019 - Mar 2020).

different conditions of the calibration procedure (for instance, the light source) can bias the PMT gain determination and impact on the results. Despite these factors, overall, a very reasonable correlation has been achieved.

6.4.3 Gain calibration with the alternative LCS

The alternative system installed in ProtoDUNE-DP, based on two fibers at the top of the cryostat, is also employed to calibrate the PMTs and the results are compared with the ones from the baseline LCS. As explained in Section 4.9.2, the alternative LCS aims to reduce the total number of fibers and feedthroughs (and, thus, the cost) in future large detectors at the DUNE scale. However, the setup required to validate such a configuration (where light must travel more than 6 m in LAr before reaching the PMTs) is complex and expensive. As the detector also counts on a reliable baseline system for the PMT calibration, the alternative LCS, not previously characterized, has been directly tested in ProtoDUNE-DP and its validation has been one of the priorities within the PDS data-taking plan.

Several complete calibrations (gain-voltage curves) were preformed on the same day using the baseline and the alternative systems. The standard data taking conditions were

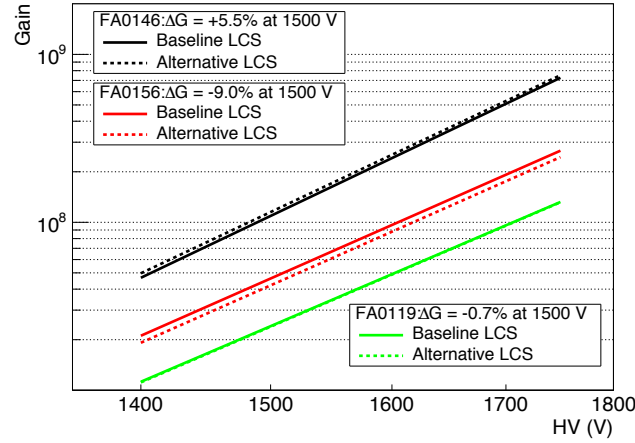


FIGURE 6.23: Comparison of the gain-voltage curves obtained with the baseline LCS (usual conditions) and the alternative LCS (top-fiber #0 with LED at 12 V) for three PMTs.

used and, in the case of the alternative system, a scan on the LED voltage (one value per calibration) was performed in order to achieve the calibration of the maximum number of PMTs possible. The gain determination is done as usual. According to the drawing in Figure 4.17 right, the top fibers are named as top-fiber #0 (left) and top-fiber #1 (right). With the top-fiber #0 (left) the 36 PMTs can be illuminated at the SPE level and properly calibrated with a LED voltage of 12 V whereas with top-fiber #1 (right) two voltage levels are needed. The reason is that the top-fiber positions were not optimized before their installation and they are not symmetrically installed: the light is sent from a side of the detector so more light reaches some PMTs.

A quantitative comparison between the two calibration systems is carried out as follows: 1) the gain of each PMT at 1500 V is determined, 2) the variation between the results (PMT per PMT) is calculated, and 3) the average of the 36 PMTs is obtained: $-9 \pm 7\%$ (alternative with respect to baseline configuration). The same procedure is followed with the HV required for a 10^7 gain, reaching a result of $-7 \pm 9\%$. The calibration curves obtained with the baseline and the alternative systems for three representative PMTs can be seen in Figure 6.23.

In conclusion, it is possible to calibrate all the PMTs with one top-fiber (~ 6 -m above the PMTs) and a single light level (LED voltage). The alternative LCS is validated since the gains obtained are compatible with the ones from the baseline calibration. Although the fiber position and the diffusion of the light need to be further studied and optimized, the alternative configuration should be considered for future LAr detectors in view of its excellent performance in ProtoDUNE-DP.

Light simulation in ProtoDUNE-DP and DUNE-DP

“ *A good simulation gives us a sense
of mastery over experience.*

— Heinz Pagels

7.1 Introduction

The detailed simulation of the ProtoDUNE-DP PDS response to cosmic muons plays an essential role to validate the results and conclusions discussed in Chapter 8. In addition, simulation studies on the PDS-based supernova neutrino trigger with the proposed DP DUNE far detector are presented in Chapter 9. The steps of the light simulation chain in LArSoft, a dedicated software for LAr TPCs (Section 7.2), are reviewed in this chapter for cosmic muons in ProtoDUNE-DP (Section 7.3) and for supernova neutrinos in DUNE-DP (Section 7.4).

7.2 LArSoft framework

The Liquid Argon Software (LArSoft¹) [166] is a physics software package designed for LAr neutrino experiments. Likewise, LArSoft is a collaboration integrated by experiments, laboratories and university groups working together to develop, improve and share a common set of software tools for simulation, reconstruction and analysis in their respective experiments. The code is written in C++ and built on the ROOT² [167] data analysis software and the *art*³ event-processing framework supported by Fermilab. The LArSoft toolkit has been validated in experiments like ArgoNeuT, LArIAT, MicroBooNE and SBND, and it is extensively used by the DUNE collaboration for simulation and reconstruction.

¹<https://larsoft.org>

²<https://root.cern>

³<https://art.fnal.gov>

7.3 ProtoDUNE-DP light simulations

The standard scintillation light simulation in LArSoft comprises three steps: 1) light generation, 2) light propagation through the detector medium, and 3) PDS response or light detection.

7.3.1 Event generators

Cosmic rays [168] are generated to mimic the data taken by ProtoDUNE-DP. Muons, electrons, positrons and gammas (electromagnetic showers) along with pions, kaons and nucleons (hadronic showers) are the major components of the cosmic rays at the Earth's surface. Muons, mainly produced by decaying charged pions ($\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$), are the most abundant charged particles in cosmic rays at sea level, being the muon flux modulated with the zenith angle, θ , as $\propto \cos^2\theta$ [169].

The scintillation light produced by cosmic muons in ProtoDUNE-DP is simulated using two particle generators to reproduce the data taken in random-trigger and CRT-trigger modes: CORSIKA and CRTGen, respectively. Their basic features along with the main assumptions in the simulation of the light production are described here. More details on the particular Monte Carlo (MC) samples will be given in Chapter 8. Note that backgrounds from natural radioactivity are not taken into account.

7.3.1.1 CORSIKA

The simulation of the cosmic-induced particles reaching ProtoDUNE-DP is based on CORSIKA (COsmic Ray SIMulation for KAscade) [170], a MC-based simulation package. Although protons (74%) comprise the major component of primary cosmic rays, other primary types are considered in CORSIKA using the constant mass composition (CMC) model [171, 172] for a more complete modelling of the flux. This multi-component model relies on the extrapolation of direct measurements of particle energy and mass spectra, and assumes the same spectral slope for all particles. According to the CMC model, the primary cosmic-ray flux, $\Phi(E)$, can be modelled as:

$$\Phi(E) = K \cdot \left(\frac{E}{1 \text{ GeV}} \right)^{-2.7} \quad (7.1)$$

where K is the flux normalization and E is the energy. The simulated primary particles (mass groups), the K parameter values and the energy range for each group are given in Table 7.1. The content of each primary source in the final flux is proportional to the shower flux normalization constant. The FLUKA model [173] describes the hadronic interactions in the shower.

Table 7.2 contains some configuration parameters of the CORSIKA-based simulation for ProtoDUNE-DP. The detector location is taken into account: CERN latitude, longitude and altitude. Namely, the first two parameters are included as the vertical and horizontal

Mass group	A	K ($\text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{GeV}^{-1}$)	Minimum energy (GeV)
p	1	1.72×10^4	1.3
He	4	9.20×10^3	5.2
CNO	14	6.20×10^3	18.2
Mg-Si	28	9.20×10^3	31.2
Fe	56	6.20×10^3	72.8

TABLE 7.1: Shower normalization constants K of the primary cosmic-ray spectrum. A is the average mass number per group. The maximum energy for all the groups is 10^5 GeV.

Stage	Parameter	Value
CORSIKA	Elevation above sea level	455 m
	Magnetic field north-component*	$22.366 \mu\text{T}$
	Magnetic field vertical-component*	$50.628 \mu\text{T}$
LArSoft	Height above TPC	506cm
	LAr bulk	$855 \times 855 \times 790 \text{ m}^3$

TABLE 7.2: Configuration of the CORSIKA-based event generation in LArSoft. The CORSIKA stage refers to the shower generation from primary cosmic-ray particles (conditions of the pre-generated samples employed by several experiments based at CERN) whereas the LArSoft stage concerns the simulation of the dedicated MC sample produced here for ProtoDUNE-DP. *Calculated with the program *Geomag* by NOAA [174].

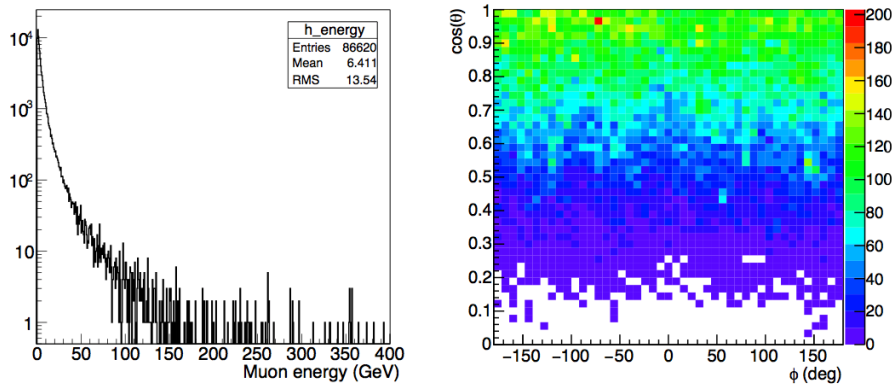


FIGURE 7.1: Left: Energy distribution of cosmic muons reaching the detector in the MC simulation with CORSIKA. The average muon energy is about 6 GeV. Right: Cosine of the zenith angle versus the azimuthal angle for the CORSIKA simulated cosmic muons.

geomagnetic field components at that location. The LArSoft simulation feeds on a random set of pre-generated air showers from a specific database created with CORSIKA. The actual number of showers per event and per source is extracted according to a Poisson distribution around the predicted average number of primary cosmic rays for that source. The simulated particles intersect the LAr bulk (inner cryostat volume) and appear to come from a certain height above the TPC during a configurable time of exposure. The start

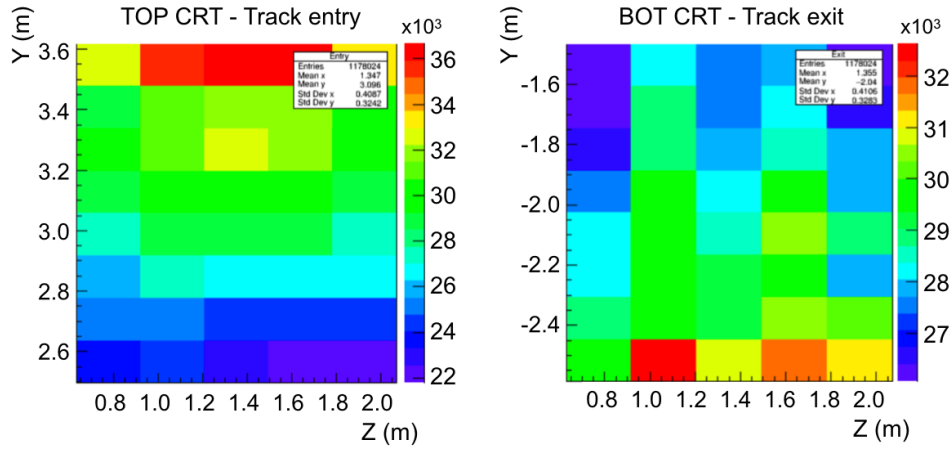


FIGURE 7.2: Entry (left) and exit (right) coordinates of the CRT-trigger tracks collected in data (CRTGen input).

time and spatial origin of the cascades of secondary particles are chosen randomly, and time and space correlations of the particles within each shower are preserved.

The energy distribution of the generated CORSIKA muons can be seen in the left panel of Figure 7.1 left, whereas the right panel shows the phase space of the muon tracks.

7.3.1.2 CRTGen

The CRTGen module is a dedicated event generator specifically created in LArSoft to simulate muons crossing the CRT panels of ProtoDUNE-DP. CRTGen calls to the SingleGen module [175], which can generate single muons (or other particles) with a defined initial position, momentum, and momentum spread. The energy distribution of the muons is taken from CORSIKA (Figure 7.1 left) for a more realistic outcome, albeit CRT-triggered muons are expected to be among the more energetic ones.

CRTGen takes the data-driven track entry/exit distributions at the CRT panels as inputs to define the track topology of the events (see Figure 7.2). However, not all the simulated muons cross both CRTs: the initial momentum of the particle starts at the top CRT and points to the bottom one, but deviations from the ideal straight trajectory can appear during the propagation through the detector and muons can decay along the track length. Thus, a topological selection is carried out and only muons with a complete trajectory between the CRTs are accepted.

7.3.1.3 Simulation of the light production

The cosmic muons simulated with the aforementioned event generators (CORSIKA and CRTGen) enter the LAr volume and deposit energy along their tracks as they interact with LAr. An incident muon behaves as a minimum ionizing particle (MIP) and deposits about 2 MeV/cm. First, the simulation of the muon energy deposition is performed by Geant4 [176]. Then, the deposited energy is multiplied by a light yield of 40k scintillation photons

Parameter	Value
MIP energy deposition in LAr	2 MeV/cm
Light yield (null drift field)	40k photons/MeV

TABLE 7.3: Parameters of the light production simulation in ProtoDUNE-DP.

per MeV to compute the amount of scintillation photons generated at each point of the LAr volume. Such an initial light yield value assumes null drift field to match the most-common data-taking conditions, which would allow the full recombination of the ionized charges. The main assumptions at this step are displayed in Table 7.3.

Note that the kind of process that produces the scintillation light is not distinguished in the MC (either direct excimer de-excitation or recombination); simply, the deposited energy is converted into VUV photons. The impact of the impurities in LAr is not taken into account in the simulation of the light production. The time profile is simulated with an exponential fast decay of 6 ns for 30% of the photons, and an exponential slow decay of 1590 ns for the other 70% of the photons; no intermediate component is included.

7.3.2 Light propagation in Geant4

The second simulation step consists in the light propagation in LAr, from the production point to the PMT array. The simulation of the particle propagation through LAr is performed with Geant4 in LArSoft. Some of the parameters assumed at this point are listed in Table 7.4. The VUV-light attenuation due to absorption by impurities in LAr is accounted for (20 m of absorption length, conservative value equivalent to 3 ppm of nitrogen contamination in LAr [177]) as well as the Rayleigh scattering effect (99.9-cm length as baseline value [77], but also a shorter length of 61 cm, motivated by [101], [102] and [96], is tested).

7.3.2.1 Detector geometry and reflectivity

The ProtoDUNE-DP geometry is modelled and implemented in Geant4 geometry-description-markup-language (GDML) files, including the full cryostat, cathode, FC, LEMs, ground grid and 36 PMTs as major elements affecting to the light propagation (see Figure 7.3). The coordinate system used for ProtoDUNE-DP in LArSoft is the one already shown in the

Parameter	Baseline value	Alternative
Absorption length	20 m	–
Rayleigh scattering length (VUV)	99.9 cm	61 cm
VUV Reflectance	26% in Al & SS, 0% for the rest	0% for all
Voxel size (x×y×z)	0.34×0.32×0.34 m ³	–

TABLE 7.4: Parameters of the light propagation simulation in ProtoDUNE-DP (Geant4 step).

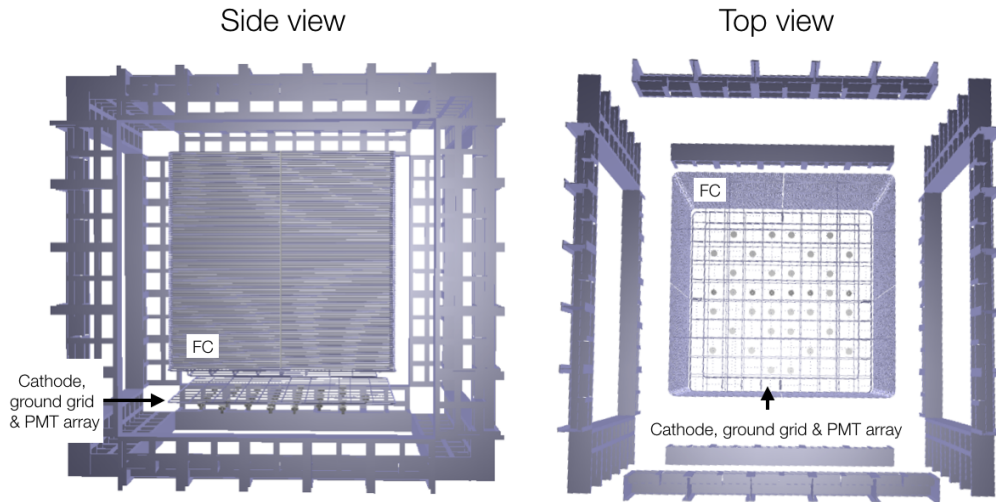


FIGURE 7.3: Views of the ProtoDUNE-DP geometry implemented in the GDML files. Some detector components (like the LEMs) are not visible here to allow the visualization of others.

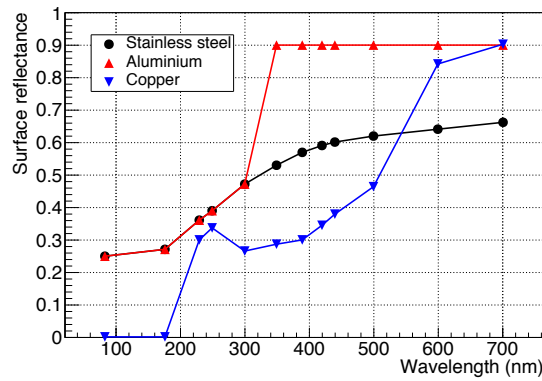


FIGURE 7.4: Reflectance factors as a function of the light wavelength for three materials [178]: stainless steel, aluminium and copper. At 127 nm, the surface reflectance for both stainless steel and aluminium is 26% whereas for copper (LEMs, for example) is null.

schematics of Figure 4.2 and the selected geometry corresponds to a vertical drift in the y-axis.

Most of the surfaces of the detector components are assumed to be fully light-absorptive (photons are removed if they reach them), except for the cryostat walls (made of stainless steel, SS), the FC (aluminium), the cathode (SS) and the ground grid (SS) whose reflectivity for VUV-light is considered in the photon library. Note that the material reflectivity can strongly vary from one manufacturer to another. It is considered a VUV reflectance of 26% for aluminum [178], as measured by the ICARUS experiment and also used by the SBND collaboration (a forthcoming short-baseline neutrino experiment), and the same VUV reflectance is assumed in stainless steel surfaces since no measurements were found. Two configurations are studied, as summarized in Table 7.4: 1) 26% of VUV reflectance only for the aforementioned components made of aluminum and stainless steel, see Figure 7.4,

and 2) null VUV reflectance for all surfaces. Therefore, in the first scenario (baseline case), the PMTs receive both direct and reflected VUV-light contributions.

7.3.2.2 Photon libraries

The complete simulation of all the photons produced by each particle crossing the detector would require an enormous CPU power and time. Hence, pre-generated maps are employed to simulate the light propagation in an efficient way: a Geant4-driven simulation is generated only once and the results (mainly, number of collected photons per PMT and propagation time) are stored and parametrized in the so-called photon libraries. This approach is viable thanks to the isotropic photon emission, and to the uniform and symmetric detector. The LAr volume is divided into 3D voxels (size given in Table 7.4) and 10^8 photons per voxel are isotropically and uniformly generated. A photon library contains, for each PMT-voxel combination: the visibility (photon detection probability), the minimum time for the light to reach the PMT (arrival time), and the Landau-fit parameters of the propagation time distribution. In order to mitigate the relatively large size of the voxels, 3D interpolations among them are done at each step of the track.

In total, three different photon libraries have been generated in order to study the impact of several parameters in ProtoDUNE-DP, as displayed in Table 7.4: A) the baseline photon library with 99.9-cm Rayleigh scattering length (RSL) and 26% of VUV-light surface reflectance, B) one with 61-cm RSL and 26% of surface reflectance, and C) one with 99.9-cm RSL and no reflections. Results will be reported in the next chapter. The maps with the detected light per deposited MeV across the volume for the baseline photon library A) are displayed in Figure 7.5 and show the detection pattern across the TPC.

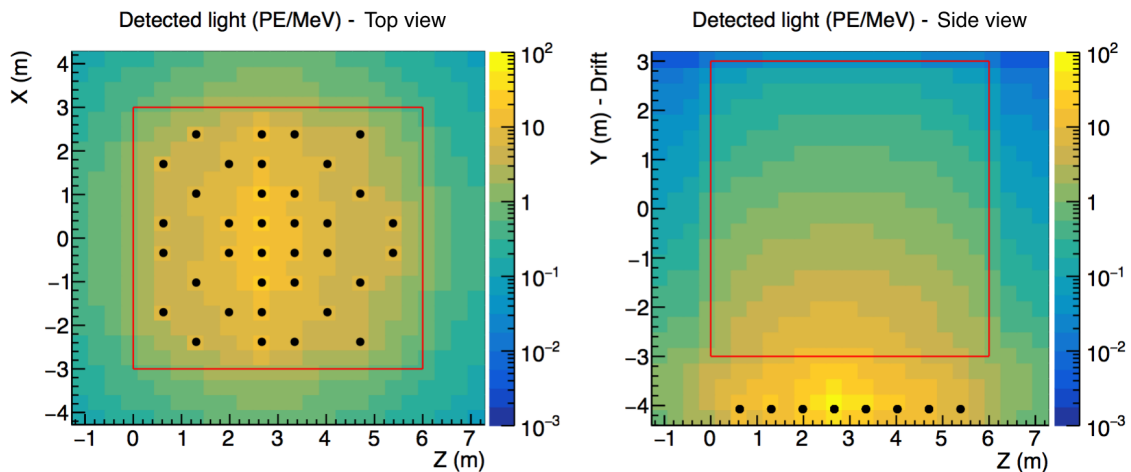


FIGURE 7.5: Maps of the detected light (sum of PMT visibilities multiplied by the PMT efficiencies used in the light simulation, $E_{TPB} = 0.090$ and $E_{PEN} = 0.016$) per voxel for the baseline photon library A) in ProtoDUNE-DP: 40k photons per MeV, 99.9 cm of RSL and VUV reflections. The PMT positions are represented with black dots and the active volume with a red-border rectangle.

Parameter	Baseline value	Alternative
PMT dark current	1.7 kHz	–
Electronic noise	0.8 ADC RMS	–
Digitalization rate	62.5 MHz	–
TPB PMT efficiency	0.090	0.099(+10%), 0.081(-10%)
PEN PMT efficiency	0.016	0.018(+10%), 0.014(-10%)

TABLE 7.5: Parameters of the light detection (PDS response) simulation in ProtoDUNE-DP.

7.3.3 PDS response simulation

Some of the parameters involved in the light detection simulation, third and last step of the chain, are shown in Table 7.5. The simulated PMT response is linear and it is produced with a dedicated module that produces a waveform for each PMT. Waveforms are generated by adding the SPE response for each detected photon. They include a dark current component of 1.7 kHz (from [118]) and 0.8 ADC counts RMS of electronic noise (from [85]). The waveform digitalization considers a 16-ns sampling in correspondence with the DAQ system. From the point of view of the scintillation light profile, both the fast and slow components (from de-excitation of singlet and triplet states, respectively) are contained in the simulated S1 signals, as explained in Section 7.3.1.3.

7.3.3.1 PMT detection efficiency

A critical aspect in the MC is the effective detection efficiency assigned to the PMTs, which depends on the WLS configuration. ProtoDUNE-DP used PEN as WLS for the first time in a large scale experiment and also the widely used TPB. Thus, results of interest are expected from comparing the efficiencies of PMTs with the novel and the mature methods in data as well as from the validation with the MC simulation.

Concerning the MC, the Geant4 simulation provides the number of VUV photons from the photon library at the WLS material, either PEN or TPB. Each VUV photon arriving to the WLS has a probability to produce a photoelectron in the PMT photocathode. This WLS-PMT photon-detection efficiency takes into account: 1) the WLS efficiency (ε_{WLS}), 2) the propagation of the visible light from the WLS towards the photocathode ($\varepsilon_{geo,WLS}$), and 3) the PMT quantum efficiency ($QE[PMT]$), considered stable when going to CT [163]. Based on the analysis presented in [146], the effective efficiency values (E_{WLS}) used in the light simulation are obtained as follows:

$$E_{TPB} = \varepsilon_{TPB} \times \varepsilon_{geo,TPB} \times QE[PMT] = 1.00 \times 0.5 \times 0.18 = 0.090 \quad (7.2)$$

Factor	Description	Value	Source
ε_{TPB}	WLS efficiency	1.00	[85]
$\varepsilon_{PEN/TPB}$	Relative WLS efficiency	0.35 ± 0.09	ProtoDUNE-DP light data [146]
$\varepsilon_{geo,TPB}$	Geometrical loss (coating)	0.5	Isotropic re-emission
$\varepsilon_{geo,PEN}$	Geometrical loss (foil)	0.247	Simulation [146]
$QE[PMT]$	PMT QE at 430 nm	0.18 ± 0.01	Hamamatsu (3 PMTs at RT)

TABLE 7.6: Factors involved in the determination of the TPB and PEN PMT efficiencies employed in the light simulation of ProtoDUNE-DP.

$$\begin{aligned}
 E_{PEN} &= (\varepsilon_{TPB} \times \varepsilon_{PEN}/\varepsilon_{TPB}) \times \varepsilon_{geo,PEN} \times QE[PMT] = \\
 &= (1.00 \times 0.35) \times 0.247 \times 0.18 = 0.016 \quad (7.3)
 \end{aligned}$$

where a 100% TPB efficiency is assumed. The different factors and their sources are summarized in Table 7.6.

In this way, $E_{TPB} = 0.090$ and $E_{PEN} = 0.016$ are obtained for TPB and PEN PMTs (included in Table 7.5), respectively, being the TPB coated-PMT six times more efficient. However, it must be considered that having the PEN foil directly over the PMT glass, as the TPB coating, would double its effective efficiency. As it will be discussed in the next chapter, two alternative efficiency values per WLS ($\pm 10\%$) are tested to investigate the impact of this parameter on the results.

7.4 DUNE-DP light simulations

As in ProtoDUNE-DP, the light simulation in the projected DP DUNE far detector can be divided into three stages: light generation, propagation and detection.

7.4.1 Event generators

The simulation studies presented in Chapter 9 focus on the light-based trigger capabilities for the supernova burst neutrino detection with a 12-kt LAr TPC as the DP DUNE far detector module. These DUNE studies were carried out for the Technical Design Report (TDR) [179] of the experiment⁴. In order to develop such an investigation, the simulations of both supernova neutrinos and detector backgrounds are required.

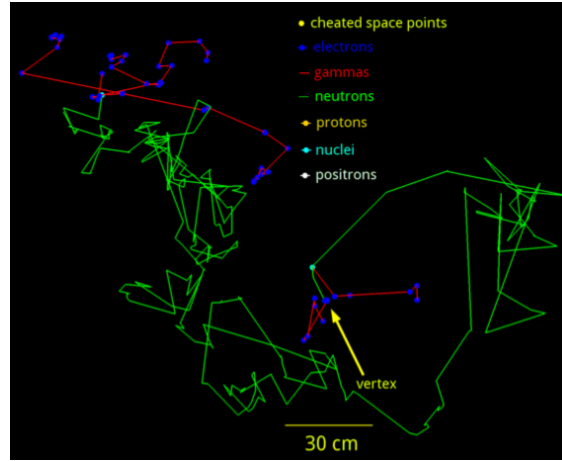


FIGURE 7.6: Visualization of trajectories and energy depositions in a typical ν_e CC event simulated with MARLEY in LArSoft [180].

7.4.1.1 MARLEY

Model of Argon Reaction Low Energy Yields (MARLEY) [180, 181] is an open-source community toolkit to model tens-of-MeV neutrino interactions on argon. This MC generator has been employed within LArSoft framework to simulate ν_e CC interactions (dominant process), $^{40}\text{Ar}(\nu_e, e^-)^{40}\text{K}^*$, in the typical energy regime of supernova neutrinos (5-100 MeV) and using the Livermore flux model [182]. Figure 7.6 shows the visualization of an example event.

The calculations performed by MARLEY are based on theoretical estimations, measurements of supernova neutrinos from SN1987A, and nuclear models. First, the incident neutrino energy spectrum is weighted using the corresponding cross section to create a distribution of reacting neutrinos energies. Then, the MC generator defines the initial excited state of $^{40}\text{K}^*$ and the electron kinematics. The direction of the ejected electron is obtained from the ν_e CC differential cross section for every particular nuclear level. This estimation relies on tabulated values of the Fermi and Gamow-Teller matrix elements. Finally, the products of the $^{40}\text{K}^*$ nuclear de-excitation are handled by MARLEY in the following way. On the one hand, if the residual nucleus is in a bound state, transitions to the ground state are sampled using tables of gamma-ray branching ratios. On the other hand, when the nucleus is in an unbound state, the decay widths of the Hauser-Feshbach model (commonly used for modeling low-energy nuclear cross sections) are employed to sample an exit channel.

7.4.1.2 Radiologicals

A MC simulation of the natural radioactivity at the FD module is key to understand the impact of the background low-energy photons on the DUNE low-energy physics. A

⁴Namely, the studies are contained in the TDR volume on the *DUNE Far Detector Dual-phase Technology* and is still to be published.

Background	Main source(s)	Activity/flux
Ar-39	LAr bulk	1.01 Bq/kg
Ar-42	LAr bulk	92 μ Bq/kg
Kr-85	LAr bulk	115 mBq/kg
Rn-222	Cryostat materials, dust contamination	40 mBq/kg
Neutrons	Rock, concrete, cosmic-ray muons	$10^{-5} \text{ cm}^{-2}\text{s}^{-1}$

TABLE 7.7: Background components of the radiological model employed for the DUNE-DP light simulation.

Parameter	Value
MIP energy deposition in LAr	2 MeV/cm
Light yield (nominal drift field)	24k photons/MeV

TABLE 7.8: Parameters of the light production simulation in DUNE-DP.

DUNE-specific radiological model with the main expected sources is employed to generate background events [183]. Note that the radiological model that was available in LArSoft at the time of the TDR preparation has been used and not later upgraded versions of the model. The model comprises (see Table 7.7): ^{39}Ar , ^{85}Kr , ^{42}Ar and ^{222}Rn radio-isotopes, being the first two nuclides the most important contaminants in commercial LAr. Besides, an impinging neutron flux reaching the detector is included in the MC sample. More details on the particular radiological sample under study will be given in Section 9.2.

The studies reported in this chapter were carried out with the DUNE-specific radiological model that was available in LArSoft when the studies for the Technical Design Report were developed. However, the model has been upgraded since then in parallel to the progress on the detector design optimization to mitigate backgrounds. Thus, the simulation studies on the SNB trigger could be repeated with an updated background sample.

The major activity is expected to come from β decays of ^{39}Ar ($^{39}\text{Ar} \rightarrow ^{39}\text{Kr} + e + \bar{\nu}_e$), albeit neutrons (difficult to shield) are also a critical background contribution as they induce gamma cascades when they are captured. It is worth noting that the understanding of the backgrounds is fundamental to develop the science program of DUNE [110], including the supernova neutrino detection.

7.4.1.3 Simulation of the light production

The scintillation light from the generated events (particles involved in the interactions with LAr) is simulated in this first stage and is later propagated and collected in the next steps. The same procedure of the ProtoDUNE-DP case (see Section 7.3.1.3) is followed here: particles (either neutrinos or radiologicals) deposit energy within the LAr bulk (simulated in Geant4) and, then, the number of scintillation photons that is generated at each point is computed by applying the light yield at the nominal drift field (500 V/cm).

Parameters are given in Table 7.8. The S2 signal is not included in the simulation because the average visibility in the gas phase is very low but still it makes the simulation much heavier. Therefore, the results that will be presented in Chapter 9 are not exclusive of the DP design.

7.4.2 Light propagation in Geant4

The Geant4-based simulation of the light transport through the DUNE-DP detector is efficiently performed using photon libraries as in the ProtoDUNE-DP case (see Section 7.3.2.2). Since a larger volume must be covered, a voxel size of 1 m^3 is employed. Other parameters of the light-propagation step are included in Table 7.9. It is worth commenting the following aspects:

- The Rayleigh scattering length for VUV light is set to 61 cm (value based on the results reported in [101], [102] and [96]).
- No Rayleigh scattering for visible light is simulated; it could occur once light has propagated through hundreds of meters of LAr, so beyond the detector dimensions.

It has to be pointed out that the simulated photon propagation in DUNE-DP is done only through the active volume (LAr region with uniform drift field). As a consequence, the light that would be collected from the LAr buffer between the field cage and the PMT array (about $1 \times 12 \times 60 \text{ m}^3$ of LAr) is not taken into account in the MC and such a light contribution is missed.

As explained before, the detector geometry is contained in GDML files (see Figure 7.7), including the main elements of DUNE-DP that are relevant for the light propagation: cryostat vessel ($\sim 15 \times 15 \times 62 \text{ m}^3$), cathode, FC, LEMs, ground grid, and 720 TPB-coated PMTs. All the detector materials are fully light-absorptive, except for the reflector foils that will be described in the next section.

It is remarkable that, in contrast to other analyses within DUNE where a reduced geometry or *workspace* is considered, here the full active volume ($\sim 12 \times 12 \times 60 \text{ m}^3$) is simulated for a more realistic outcome since in the DP design there is not any optical segmentation. In the coordinate system used in the DUNE-DP simulations, the vertical drift is along the x-axis and the neutrino beam is aligned with the z-axis.

Parameter	Baseline value	Alternative
Rayleigh scattering length for VUV light	61 cm	–
Absorption length (all λ)	20 m	–
WLS reflective foil coverage	Half	Full, none
Foil WLS efficiency for VUV light	100%	–
Foil reflectivity for visible light	93%	–
Voxel size	$1 \times 1 \times 1 \text{ m}^3$	–

TABLE 7.9: Parameters of the light propagation simulation in DUNE-DP (Geant4 step).

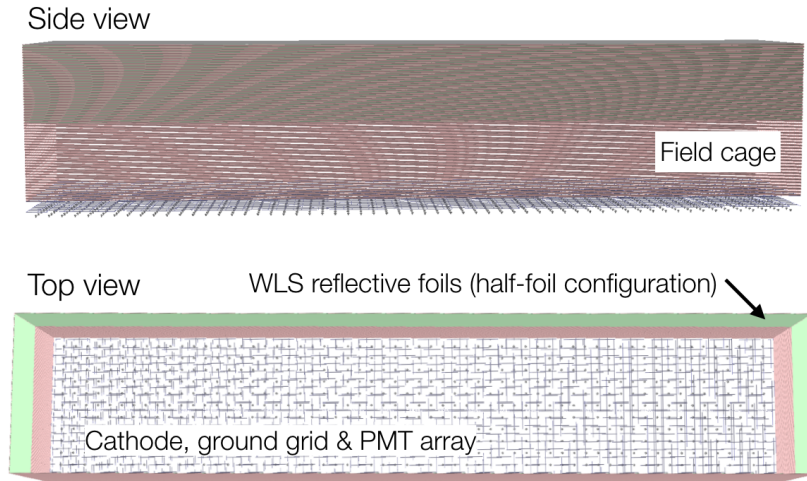


FIGURE 7.7: Views of the DUNE-DP geometry implemented in the GDML files (half-foil scenario). Some detector elements are not visible to allow the visualization of the others.

7.4.2.1 WLS reflective foils

The impact of having TPB-coated reflective panels (also referred-to as WLS reflective foils) is investigated with dedicated simulations [179]. The envisioned foils (see details in Section 3.2.3.2) could cover partially or completely the inner FC walls. Thus, three foil-scenarios are compared: 1) without foils (no-foil configuration), 2) foils only on the top half of the FC (half-foil configuration, baseline), and 3) FC inner walls entirely covered with foils (full-foil configuration). A different photon library for each foil geometry is required. As shown in Table 7.9, the TPB-coated foils are assumed to have a WLS efficiency of 100% for VUV light, and a reflectivity for visible re-emitted light of 93% [142].

Figure 7.8 shows the distributions of the detected light (sum of PMT visibilities multiplied by the light yield and by 0.12 of effective PMT efficiency) along the drift (vertical)

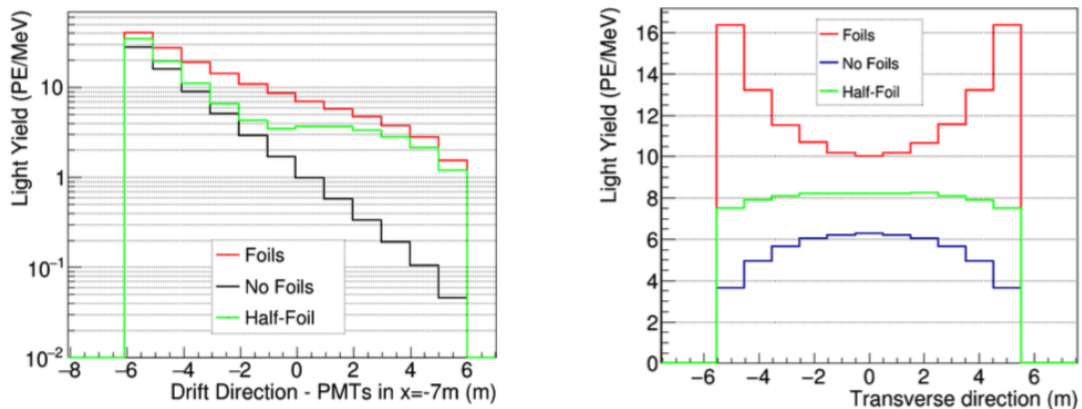


FIGURE 7.8: Expected detected light (PE per deposited MeV) in DUNE-DP. The yields along the drift (left panel) and transverse (right panel) directions are displayed, averaging over the other two directions in each case. Three foil-configurations are compared (described in the text): no-foils (black or blue), half-foils (green) and full-foils (red).

Parameter	Value
PMT dark current	1.7 kHz
Electronic noise	0.8 ADC RMS
Digitalization rate	250 MHz
PMT efficiency for VUV light	0.12
PMT efficiency for visible light	0.20

TABLE 7.10: Parameters of the light detection simulation in DUNE-DP.

and transverse (horizontal and perpendicular to the neutrino beam line) directions. The yield is averaged over the other two directions in each case. The higher light level with foils is because more photons reach the PMTs: almost 11.3% (33.8%) of the photons collected by the PMTs with half (full) foils are visible light. As a result, the overall light level increases. It is especially important the enhancement of PMT visibility that the foils provide in the top half of the detector volume (Figure 7.8 left), which is the less efficient region in terms of light detection. Besides, the half-foil geometry allows to improve the uniformity of the detected light yield along the transverse direction (Figure 7.8 right).

7.4.3 PDS response simulation

Table 7.10 summarizes the assumptions made in the simulation of the light detection with the PMTs of DUNE-DP. Some of them are the same already explained for the ProtoDUNE-DP simulation (dark current [118] and electronic noise [85]), while others are exclusive of the DUNE setup, like the higher digitalization rate (4-ns sampling). The PMT response at the SPE level at a 10^7 gain follows the observed PMT behaviour in the laboratory: 6-ns time width and 15-mV (30 ADC counts) amplitude pulses.

Concerning the photon collection, effective PMT efficiencies (WLS+coating+QE) of 0.12 [147] and 0.20 (Hamamatsu specifications) are considered for VUV light and visible photons, respectively. The TPB coating either on the PMT photocathode or the reflective panels is assumed to convert all the VUV photons into visible light (100% efficient). Nevertheless, the re-emission of photons by the TPB coating on the PMT is isotropic (upwards or downwards photons) and, hence, only a fraction of the VUV photons will actually reach the PMT photocathode leading to a lower probability of detection compared to the visible-light case.

Scintillation light produced by cosmic muons in ProtoDUNE-DP

“ *I would rather have questions that can't be answered
than answers that can't be questioned.*

— Richard Feynman

8.1 Introduction

The cosmic-muon data taken with the PDS of ProtoDUNE-DP provide an unique opportunity to investigate the production and propagation mechanisms of the scintillation light in LAr as well as the light collection by PMTs in the largest DP LArTPC ever operated. In addition, ProtoDUNE-DP allows for the measurement of the cosmic muon flux at ground level and the evaluation of the PDS to perform calorimetry.

In this chapter, results obtained from both PMT data and light simulation are presented and discussed. First, a data-driven characterization of the low-energy background pulses detected by the PMTs is performed (Section 8.2). Secondly, the light production, propagation and detection in LAr are investigated by selecting muon tracks crossing diagonally the detector (Section 8.3). A study of the drift field impact is carried out using PDS data and a field simulation. On the other hand, relevant information is extracted from the MC simulation on aspects like the Rayleigh scattering length, the impact of the VUV-light reflections and the PMT detection efficiency. Lastly, the collection of the scintillation light produced in the complete LAr volume is assessed in order to measure the cosmic muon flux at the detector and determine the observed light yield by the PDS (Section 8.4).

8.2 Single photo-electron characterization

8.2.1 Low-energy light sources

Small scintillation light signals are detected by the PMTs as single-photoelectron (SPE) signals. The capability of measuring low-energy signals depends on the signal-to-noise ratio and on the SPE rate. In ProtoDUNE-DP, there are several light sources that contribute to the low-energy background detected in the PMT waveforms:

- **Natural radioactivity:** different components are expected to produce low-energy scintillation light pulses in the LAr bulk. The two most-abundant isotopes in commercial LAr are ^{39}Ar and ^{85}Kr and, hence, they comprise the most significant radioactive contaminants [78, 184]. The activity of the former is 1.01 Bq/kg and the one of the latter is 115 mBq/kg. Both nuclides primarily decay by beta emission. Other radioactive isotopes such as ^{42}Ar (92 $\mu\text{Bq/kg}$) and ^{222}Rn (40 mBq/kg) have a negligible activity compared to the ^{39}Ar decay rate [185, 186]. On the other hand, neutrons captured by the detector components can induce gamma cascades that also contribute to the light background. In fact, the rock of the cavern housing DUNE FD (approximately 1.5 km underground) is expected to produce an important neutron flux. Thus, the background control is essential to accomplish the science goals of DUNE [110, 187], not being as critical at the ProtoDUNE stage.
- **Cosmic muons producing small S1 signals:** when a crossing muon either deposits a small amount of energy in LAr or interact with LAr far away from the PMT array, the corresponding scintillation light can be detected by the PMTs as SPE pulses.
- **PMT dark current:** SPE (scintillation) pulses are generated mainly by thermionic emission but also by other non-thermal processes at CT [118]. Based on the cryogenic characterization of the typical dark current of each PMT installed in ProtoDUNE-DP (see Section 5.2), a dark current rate of 1.7 kHz (average rate measured at a gain of 10^7) is expected.
- **Ions in the bulk:** a study in [67] suggests that the recombination of Ar_2^+ drifting to the cathode with electrons and the neutralization of Ar_2^+ with electric negative impurity molecules such as H_2O^- originate photons through de-excitation and could explain the high SPE rate recently measured in several experiments. In presence of an electric field, there are two competing effects (although the first one dominates): 1) the higher the field, the faster the ion transport in the drift direction and, hence, the lower the photon production rate, and 2) a higher electric field also leads to a more difficult prompt recombination of Ar^+/e^- pairs which results in more Ar_2^+ ions in the LAr bulk.
- **Other light sources:** possible light infiltrations into the cryostat and light sparks (visible light). Small amounts of light might penetrate into the detector through the instrumentation feedthroughs and the LCS optical fibers. In addition, it is known that components like the VHV extender or the CRPs produced discharges in different moments during the detector operation. Although difficult to be quantified, these contributions must be considered.

The only light background included in the MC simulation performed for the analyses discussed in this chapter is the PMT dark current contribution, whereas all the SPE sources listed above play a role in the collected PMT data. The background of single photons can limit the PDS capability for low-energy physics, not intended in ProtoDUNE-DP but envisioned in future underground LAr TPCs like DUNE.

The complete investigation of the low-energy backgrounds in ProtoDUNE-DP would require a detailed MC simulation of the natural radioactivity in the detector and is not carried out here. Nevertheless, SPE pulses in data runs are studied in order to estimate their impact on the later muon-signal analyses. A basic characterization of the SPE background is done (pulse amplitude, width and rate) as a good understanding of the SPE pulses is considered to be a fundamental step towards the more-complex studies contained in this chapter. Regarding the SPE rate, an estimation of the expected rate from the sources listed in this section will be carried out.

8.2.2 SPE amplitude and width

The SPE amplitude as a function of the PMT gain is characterized in this section. As it will be shown later in Section 8.4.2.1, the analysis on the S1 signals induced by muons is based on an amplitude threshold which is defined in terms of the SPE amplitude (and its spread) at the operating gain, so the SPE characterization developed here is critical. SPE pulses in the waveforms from calibration runs taken with the LCS (controlled SPE trigger) are considered for this data analysis. The results of the calibration itself are employed to calculate the gain at each HV. Namely, two complete calibrations (16 runs, ~ 12 M events) in the standard conditions (see Section 6.4.1) are analyzed for this purpose.

Figure 8.1 shows the SPE amplitude spectra corresponding to one PMT for the different HVs. The topology of this amplitude spectrum responds to the same physics processes

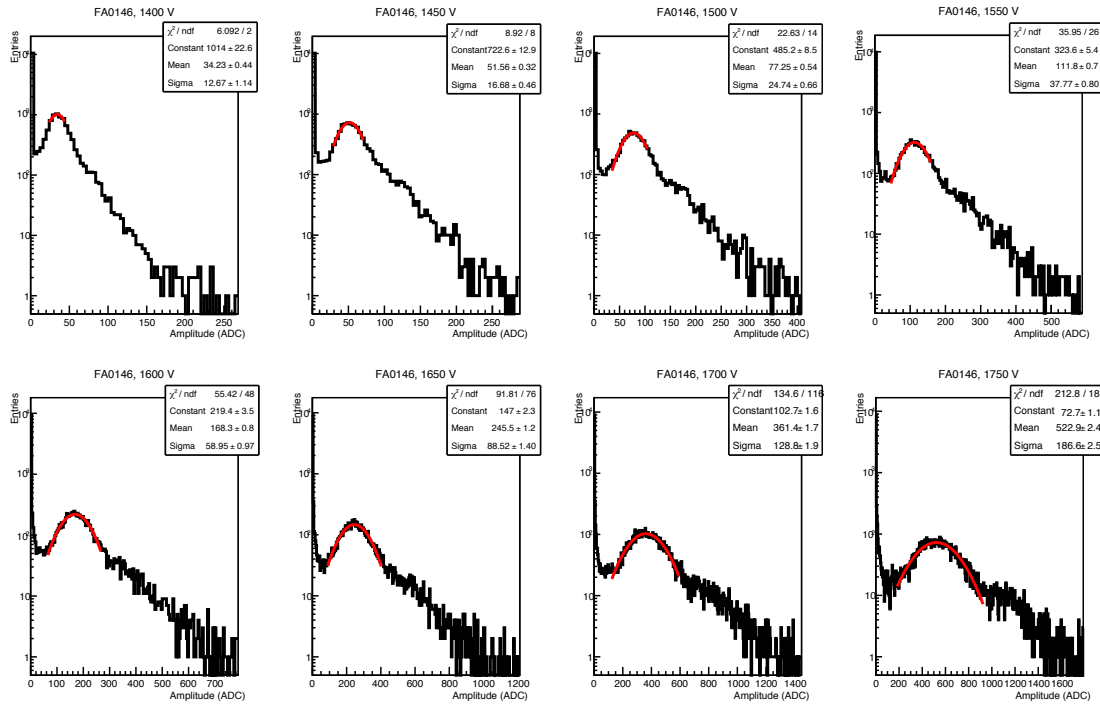


FIGURE 8.1: SPE amplitude spectra (black) for one PMT and different HVs. A Gaussian fit (red) of the SPE peak is displayed.

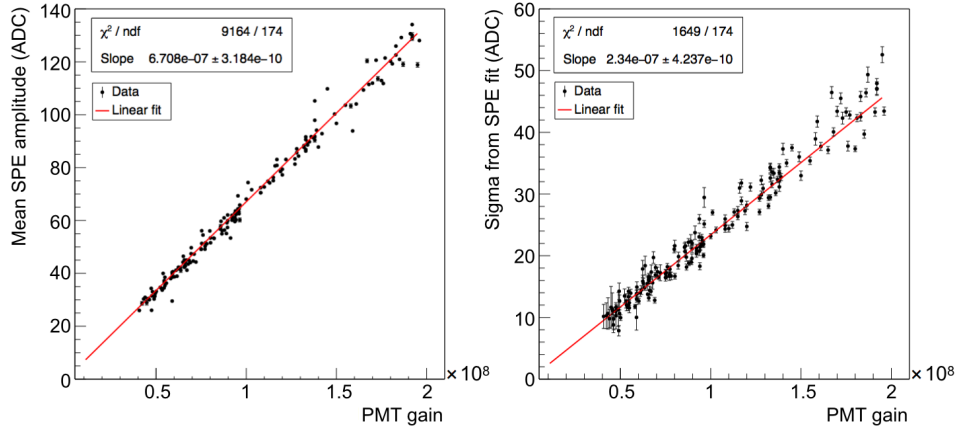


FIGURE 8.2: Mean (left panel) SPE amplitude and sigma (right panel) from Gaussian fits as functions of the PMT gain, and linear fits.

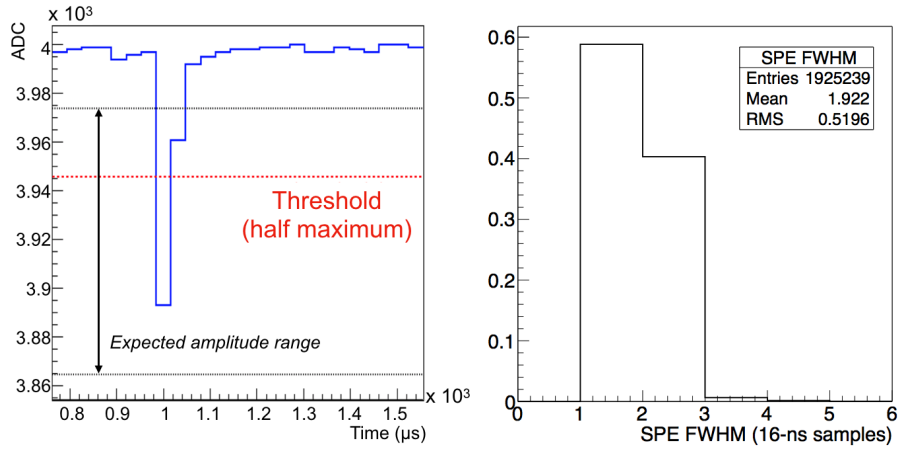


FIGURE 8.3: Left: Example of SPE pulse with FWHM of 16 ns (1 sample). Right: Normalized FWHM distribution of the SPE pulses.

than the SPE charge spectrum explained in Section 5.2.2.2: it exhibits the pedestal peak centered at 0 and a second peak corresponding to the SPE signal with a width representing the SPE amplitude spread. A Gaussian fit of the SPE peak is performed. The mean and σ from the fits as functions of the PMT gain are presented in Figure 8.2, including a linear fit of each parameter. The fits allow the interpolation or extrapolation of the average SPE amplitude and its spread at any gain. The 36 PMTs and the 16 runs are combined for a better estimation since no big discrepancies among them were found, albeit only data corresponding to gains up to $2 \cdot 10^8$ are included to ensure the PMT linear response (saturation effects are observed in some PMTs at higher gains even at the SPE level). Likewise, the amplitude spectra taken at low PMT gains that can not be properly fitted are excluded in this analysis.

In addition, the average duration of the SPE pulses in the waveform is estimated. The same calibration data used for the amplitude characterization are analyzed. The full width at half maximum (FWHM) is obtained for each SPE pulse (see Figure 8.3 left) and only

pulses with an amplitude within the expected range according to the results of Figure 8.2 are considered. As before, only PMT gains up to $2 \cdot 10^8$ are considered to guarantee the response linearity. The combination of all the PMTs and data samples gives as a result the normalized distribution presented in Figure 8.3 right, where it can be seen that most of the SPE pulses have a FWHM of 1 sample (59%, 16 ns) or 2 samples (40%, 32 ns).

According to the characterization above, the SPE pulse has a FWHM of 16-32 ns and an average amplitude (mean value plus σ) of 7 ± 2 ADC at a gain of 10^7 . This data-based result can be compared to the expected amplitude (A) in 1 sample from the DAQ features as follows:

$$A = \frac{4096 \text{ ADC}}{2 \text{ V}} \cdot (50 \Omega) \cdot (10^7) \cdot \frac{1 \text{ PE}}{1 \text{ sample}} \cdot \frac{1.602 \cdot 10^{-19} \text{ C}}{1 \text{ PE}} \cdot \frac{1 \text{ sample}}{16 \cdot 10^{-9} \text{ s}} \approx 10 \text{ ADC} \quad (8.1)$$

where $(4096/2) \text{ ADC/V}$ is the ADC dynamic range, 50Ω is the ADC terminator resistor, 10^7 is the gain, $1.602 \cdot 10^{-19} \text{ C}$ is the absolute electron charge, and $16 \cdot 10^{-9} \text{ s}$ is the sampling period. The calculation can be also done for more than 1 sample. The result of weighting the expected amplitudes by the probabilities seen in data for the different FWHM (from 1 to 3 samples) is:

$$A' = (0.5882 \times 10.25 \text{ ADC}) + (0.4031 \times 5.13 \text{ ADC}) + (0.0063 \times 3.42 \text{ ADC}) \approx 8 \text{ ADC} \quad (8.2)$$

It must be taken into account that the probability of having 1 PE contained in 1 sample is overestimated in the previous calculation: it corresponds to the FWHM of the pulse so the total SPE width can be larger (as in Figure 8.3 left). Nevertheless, the result of ~ 8 ADC is still compatible within the error with the measured amplitude (from extrapolation) at that gain.

8.2.3 SPE rate

The SPE rate measured by the PMTs in ProtoDUNE-DP has been computed by counting the SPE pulses in selected regions of PMT waveforms acquired in random-trigger mode. The goal is to determine the impact of this low-energy background in the cosmic muon studies. The excellent signal-to-noise ratio in the PMT waveforms (>11 , see Section ??) is critical for an efficient SPE pulse identification. The parts of the waveform affected by S1 signals larger than 1 PE are skipped to ensure that no pulses from S1 signals are included in the result. The basics of the SPE-finding algorithm are the following (see Figure 8.4):

1. Any signal with an amplitude in the range ($mean \pm 2\sigma$) is considered a SPE pulse. The limits of this range depend on the PMT gain: $mean$ and σ are obtained from the fits in Figure 8.2.

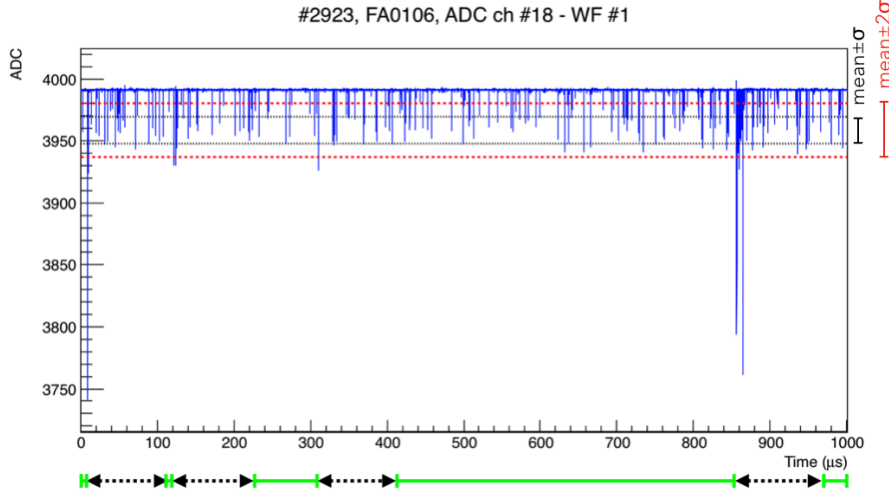


FIGURE 8.4: Example of a 1-ms event taken in random-trigger mode for a PEN PMT ($5 \cdot 10^7$ gain) and with no detector fields. The black and the red horizontal lines represent respectively the SPE amplitude limits of the $mean \pm \sigma$ and $mean \pm 2\sigma$ ranges for this particular PMT in this run. The approximate time windows considered and ignored for the SPE counting are indicated in green solid and black dashed lines below the x-axis, respectively.

2. After a SPE pulse, 32 ns are excluded from the counting in order to take into account the SPE width.
3. If a signal has an amplitude larger than $(mean + 2\sigma)$, a 100- μs window starting at the signal peak time is excluded from the SPE counting. It is considered that a potential S1 signal has been found and, following a conservative approach, the veto window is long enough to skip the complete scintillation light profile of the signal before the SPE counting is resumed.
4. During the ignored time after a S1 signal, the amplitude of the pulses is continuously evaluated, and, if a new potential S1 signal is identified during the ignored time, a new 100- μs veto window is opened from that point.
5. The rate is calculated as the number of identified SPE pulses over the effective time of counting, which does not include the dead-time windows.

First of all, the SPE rate in absence of fields is assessed. In total, 8 random-trigger runs (around one per month) are analyzed in order to estimate the average SPE rate during the detector operation. The SPE rate results (average per PMT for each WLS group) with fields off are contained in Table 8.1. The SPE rate stability with time can be seen in Figure 8.5, where the results from the 8 data sets are plotted. It can be observed that PEN PMTs are less efficient and collect only about the half of the SPE signals detected by TPB PMTs.

Two types of errors are included in Table 8.1: δ_{PMTs} comes from the dispersion among PMTs within every run (average of the values for all runs) whereas δ_{Runs} is the dispersion among runs (average of PMTs). The former error points out that the SPE detection rate is relatively uniform across the PMT array for each WLS group. On the other hand, the latter error gives an idea of the SPE rate stability: a non-negligible rate variation

WLS	SPE rate fields OFF (kHz)	SPE rate fields ON (kHz)
TPB	$345 \pm 46(\delta_{\text{PMTs}}) \pm 145(\delta_{\text{Runs}})$	$2493 \pm 595(\delta_{\text{PMTs}}) \pm 835(\delta_{\text{Runs}})$
PEN	$166 \pm 33(\delta_{\text{PMTs}}) \pm 41(\delta_{\text{Runs}})$	$1089 \pm 154(\delta_{\text{PMTs}}) \pm 117(\delta_{\text{Runs}})$

TABLE 8.1: SPE rate results for TPB and PEN PMTs in different field configurations: fields off, drift field (cathode at -50 kV)) and fields on with S2 signal production (cathode at -50 kV, grids at 6-6.2 kV and LEMs at 3.1-3.4 kV across). Regarding the errors, δ_{PMTs} corresponds to the STD among PMTs (average of dispersions in the different runs) and δ_{Runs} is the STD among runs (average of PMTs).

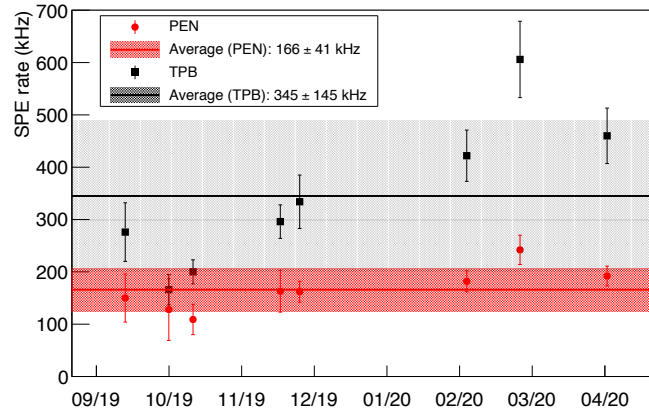


FIGURE 8.5: SPE rate stability from September 2019 to April 2020 (fields off). The average value per WLS group for each data run is displayed, and the vertical error bars represent the dispersion among PMTs (STD) within each run. The horizontal color bands correspond to the spread of the average SPE rate including all the PMT runs under study.

with time is observed, primarily for TPB, as displayed in Figure 8.5. The SPE frequency difference among runs is not completely understood, albeit its origin is possibly related to: 1) variations of the PMT response (fatigue effect, gain adjustments...), 2) an increment of the low-energy light level caused by infiltrations into the cryostat and/or light discharges, as commented in Section 8.2.1. Despite the variations, the average results given in the table are considered to be a fair estimation to understand the SPE rate impact on the S1 light studies presented in this chapter.

Taking into account the aforementioned light contributions at the SPE level, a rough estimation of the expected low-energy pulse rate includes:

- Natural radioactivity, mainly from ^{39}Ar , ^{85}Kr and ^{42}Ar , contributing with ~ 20 kHz (MC-based result from the analysis of a sample with only these three isotopes and no muons generating the light).
- The PMT dark current, adding a SPE rate of 1.7 kHz (from characterization measurements [118]).
- Scintillation signals produced by cosmic muons and detected as SPE pulses by the PMTs at ~ 35 kHz (MC-driven result from the analysis of a CORSIKA-based sample with only muons generating the light).

Although a deeper simulation study of the background signals from natural radioactivity in ProtoDUNE-DP would be required to obtain further conclusions, it is evident that the measured SPE rates without drift field ($\sim 170\text{-}350$ kHz) are higher than the expected value from these contributions (~ 60 kHz, in total). Unfortunately, the hypothesis of the light from A_2^+ recombinations [67] cannot be tested in ProtoDUNE-DP because of the non-uniform drift field. Likewise, the light infiltrations or sparks are considered an indeterminate component in this analysis.

According to the values in Table 8.1, the expected number of SPE pulses in a $4\text{-}\mu\text{s}$ window¹ of TPB PMT waveform can be calculated as:

$$N_{\text{SPE}}(\text{TPB}) = (345 \pm 136) \text{ kHz} \times 4 \cdot 10^{-6} \text{ s} = (1.38 \pm 0.54) \text{ SPE pulses} \quad (8.3)$$

whereas for PEN PMTs is:

$$N_{\text{SPE}}(\text{PEN}) = (166 \pm 38) \text{ kHz} \times 4 \cdot 10^{-6} \text{ s} = (0.66 \pm 0.15) \text{ SPE pulses} \quad (8.4)$$

Based on the calculations above, the expected impact of the low-energy background on the S1 signal charge estimation is low: $\mathcal{O}(1)$ SPE pulses per $4 \mu\text{s}$ of waveform for any WLS. However, the overall SPE pulse frequency, of the order of hundreds of kHz, can play a role in the S1 rate analysis and must be taken into account when interpreting the results that will be presented in Section 8.4. Namely, some SPE pulses with amplitude larger than $\text{mean} + 2\sigma$ are identified as small S1 signals induced by muons and contribute to the S1 rate result. In order to mitigate this issue when the S1 rate exclusively produced by cosmic muons is being studied, other conditions for a pulse to be counted in the S1 rate are applied (such as detection in coincidence among PMTs) in addition to the S1 amplitude threshold required for the signal identification.

As stated before, the non-uniform drift field along with the very few runs with only drift field (no electroluminescence) prevent from performing a complete investigation of the field impact on the SPE rate. Nevertheless, Table 8.1 also includes the results from the analysis of four random-trigger runs taken with S2 signal production to approximately determine the SPE rate change with respect to the fields-off case. The cathode was biased at -50 kV, the extraction grids at $6\text{-}6.2$ kV and the LEMs at $3.1\text{-}3.4$ kV across. These voltage conditions were relatively standard in the detector operation with fields. The SPE rate increases from hundreds of kHz in absence of fields up to several MHz when there is S2 light production. The rate variation with time (δ_{Runs} in the table) is also significant, specially for TPB PMTs in this case. Example PMT waveforms with and without S2 production can be seen in Figure 8.6. It is clear that the S2 signals are an important and continuous contribution to the low-energy background in the PMT waveform. In order to avoid this light component affecting the S1 signal reconstruction, runs without S2

¹Most-common charge integration window used in the S1 studies.

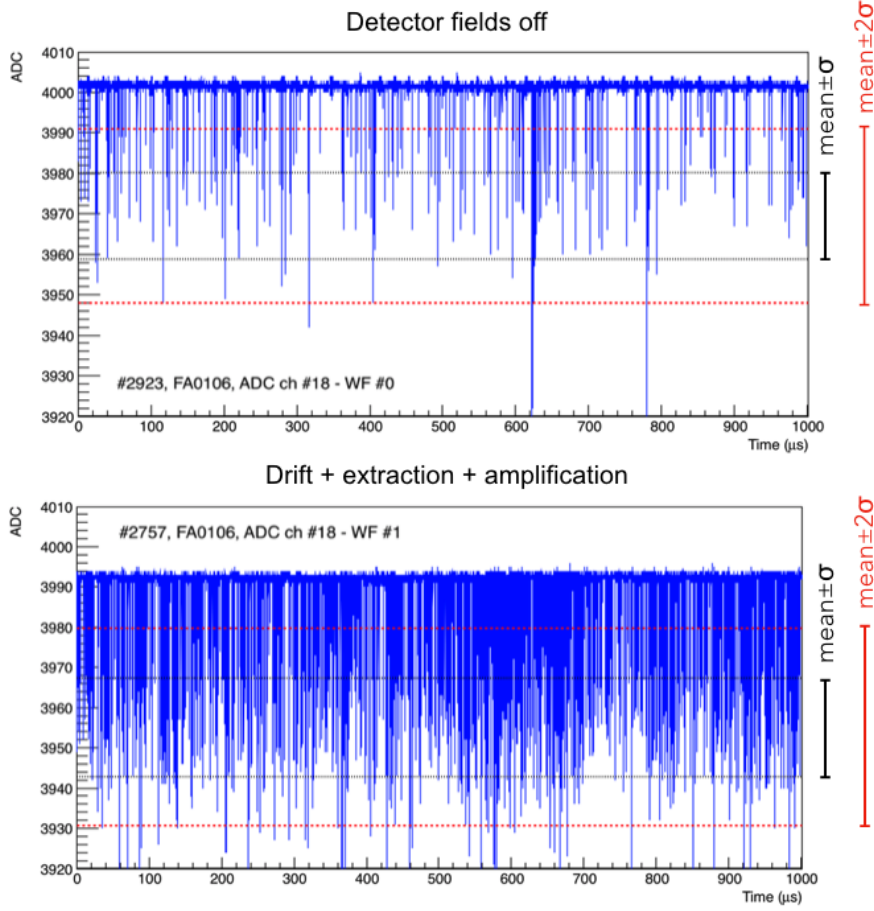


FIGURE 8.6: PEN PMT waveforms ($5 \cdot 10^7$ gain) acquired in random-trigger mode. Top panel: Run with detector fields off. Bottom panel: Run with drift (cathode at -50 kV), extraction (grids at 6.0-6.2 kV) and amplification (LEMs at 3.1-3.4kV across) fields. A zoom in the y-axis is set to focus on the SPE signals.

production will be always chosen for the S1 studies reported in the next sections of this chapter.

8.3 Study of the scintillation light in LAr

The very pure LAr of ProtoDUNE-DP is an optimal medium for the study of the scintillation light production, propagation and collection in a LAr TPC. The experiment provides valuable technical feedback for future light detection systems as well as results on the scintillation light mechanisms in LAr. PMT data acquired with the CRT-trigger system (see Section 4.7) have been analyzed to profit from the off-line reconstruction of the track trajectory such a trigger allows. Muon tracks crossing diagonally and downwards the detector are selected, and fundamental information is retrieved from the distance the light travels from its production point in the LAr volume to the PMT detecting the signal. Details

on the data runs, the MC samples, the event selection and the analysis approach followed in this analysis are given in Sections 8.3.1-8.3.3.

Besides providing an overall validation of the light simulation chain developed in LArSoft for ProtoDUNE-DP (Section 8.3.4), the studies reported in this section aim at addressing the following LAr properties and light phenomena (previously introduced in Section 2.5):

- **Light production in LAr:** 1) light yield suppression with drift field (Section 8.3.5).
- **Light propagation in LAr:** 2) Rayleigh scattering length (Section 8.3.6), 3) VUV reflectivity of the different detector materials (Section 8.3.7).
- **Light detection by the PMTs:** 4) effective PMT efficiency, including WLS conversion (Section 8.3.8).

From the point of view of the light measurements, unique results can be obtained in ProtoDUNE-DP since its drift distance (6 m) is the longest among past and current LAr TPCs and, hence, the maximum path travelled by the scintillation photons corresponds to the longest light propagation distance ever studied in this type of detector.

8.3.1 CRT-trigger: runs of interest and MC samples

The conditions of the CRT-trigger runs under study are displayed in Table 8.2. The focus is on the primary scintillation light (S1 signal) and, hence, runs without electroluminescence production (S2 signal) are chosen. One run without drift field and another with cathode at -50 kV (maximum operating HV) are analyzed to study the drift field effect. Both runs were taken on the same day and without switching the PMTs off in between. Concerning the data analyzed to compare with the simulation, they are night-runs with a duration of about 12 h, the longest PMT runs taken due to the detector constraints.

Given the good agreement observed among different gains (about 4% of dispersion in the average integrated charge, included in the errors), particular runs are selected depending on the WLS: the run at $1 \cdot 10^7$ gain is analyzed to study the response of TPB PMTs whereas the run at $2 \cdot 10^7$ is employed to obtain the PEN results. In this way, the potential saturation effects are minimized for TPB PMTs and the small pulses from distant

Goal	Run#	#Events	WLS of interest	TPB G	PEN G	Cathode HV (V)
Drift field	2553	1058	Both	$6 \cdot 10^6$	$5 \cdot 10^7$	-50
impact	2555	6730	Both	$6 \cdot 10^6$	$5 \cdot 10^7$	0
Compare	2737	18267	PEN	$2 \cdot 10^7$	$2 \cdot 10^7$	0
to MC	2743	18819	TPB	$1 \cdot 10^7$	$1 \cdot 10^7$	0
Error from G	2739	17708	Both	$5 \cdot 10^7$	$5 \cdot 10^7$	0

TABLE 8.2: Acquisition conditions of the CRT-trigger light data samples (1-ms readout window).

muon-tracks are enhanced for PEN PMTs. The run at the highest gain (#2739) is employed for the estimation of the systematic error in the charge due to the operating PMT gain.

The light simulation chain in LArSoft with the CRTGen generator module to simulate muon-like events crossing the CRT panels has been followed (see Section 7.3). The MC sample with baseline parameters contains 16k events to match the statistics in data sets after the event selection and all PMTs have a gain of $2 \cdot 10^7$ as no saturation effects are implemented. Two additional MC samples have been generated in order to test the alternative parameters already shown in the previous chapter: 1) Rayleigh scattering length (RSL) of 61 cm, and 2) null VUV reflectance in all the detector materials.

8.3.2 CRT-trigger: event selection

The charge of each triggered signal is obtained by integrating the PMT waveform in a $4\text{-}\mu\text{s}$ window around the S1 signal (Q_{total} defined in Section 6.3.2). The gain of each PMT is corrected using the closest calibration for a more accurate charge result. Then, a selection of the events is carried out, both in data and simulation to obtain comparable event samples. The selection cuts are summarized in Table 8.3, where the final fraction of events after each condition is indicated. Further descriptions of these quality and physics requirements are:

1. **Time of flight (data) / geometrical cut (MC):** a data event is considered a good muon-candidate (clean coincidence) if the time of flight between the panels (from top to bottom) is between 40 and 45 ns, and only one scintillator per panel is fired (see distributions in Figure 4.7 right). This cut contributes to the rejection of background events like electrons, particle showers, muon bundles and fake triggers. In the simulation case, only CRT-trigger-like muons are kept by requiring that the track trajectory crosses both CRTs. It can be seen in the table that the first condition is the one that mostly reduces the statistics of the final sample both in data and MC.
2. **Stable baseline before trigger:** this cut intends to avoid the pile-up of signals. The waveform RMS is obtained in a $1\text{-}\mu\text{s}$ window before the signal trigger and the baseline is considered to be stable if the result is below 1 ADC count, being this quality cut independent from the pedestal calculation explained in Section 6.3.2.

#	Requirement	Data events (%)	MC events (%)
–	No cuts: raw data or sample	100.0	100.0
1	ToF cut (data) / geometrical cut (MC)	36	43
2	Stable baseline before trigger	28	42
3	No ADC saturation	27	42
4	Maximum charge	25	39

TABLE 8.3: Average fraction of events after the selection cuts over the CRT-trigger data and baseline CRTGen MC sample.

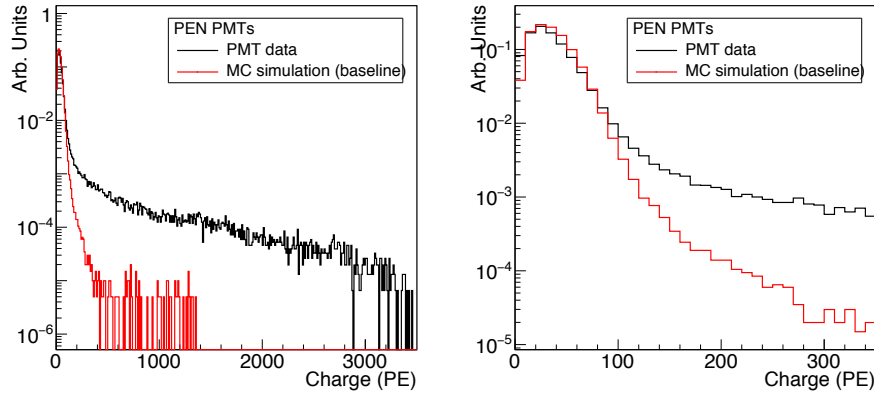


FIGURE 8.7: Charge distributions for PEN PMTs from data (CRT trigger) and MC (baseline CRT-Gen sample): complete charge range (left panel) and zoom in the x-axis (right panel); cuts 1-3 are applied.

3. **No ADC saturation:** the data events with waveforms saturating the ADC are excluded both in data and MC samples. They prevent a correct charge integration in the data case. It is found that the saturation cut, which is artificial in the case of the simulation, does not significantly reduce the statistics of MC events.
4. **Maximum charge:** the charge per event must be below 100 (400) PE for PEN (TPB) PMTs. These limits per WLS group are applied to suppress the high-energy events that affect the distribution of interest in data, but not to the MC, see charge distributions for the PEN case in Figure 8.7. This background component beyond the imposed charge limit comprises signals up to 4000 PE in data while in the simulation (clean sample of muons) the maximum charge observed is about 10 times lower.

8.3.3 Track reconstruction and analysis approach

The distributions in Figure 8.8 illustrate the track topology in data and MC. As one can see, the CRTGen custom module fairly reproduces the muon tracks crossing between the CRT panels. Only downwards tracks (zenith angle or $\theta > 90^\circ$) are allowed. The acceptance range in the azimuthal angle, ϕ , is $(82^\circ, 98^\circ)$, and the distribution peaks at $\sim 90^\circ$, as expected since the CRT panels are aligned in the z-axis (see the detector schematic in Figure 4.2). The average track length between the CRTs (~ 1270 cm) matches the panel positions. These results validate the track reconstruction as well as the data-driven muon-track topology in the simulation.

Since the propagation effects on the collected charge by the PMTs depend on their distance to the muon track, the analyses shown in the following are mainly based on the correlation between the collected S1 signal (S1 charge in PE units) and the minimum approach distance from the muon track to the detecting PMT (simply referred-to as track-PMT distance). After the event selection, 2D distributions of these variables as the ones presented in Figure 8.9 for PEN PMTs are obtained. The color scale indicates the number

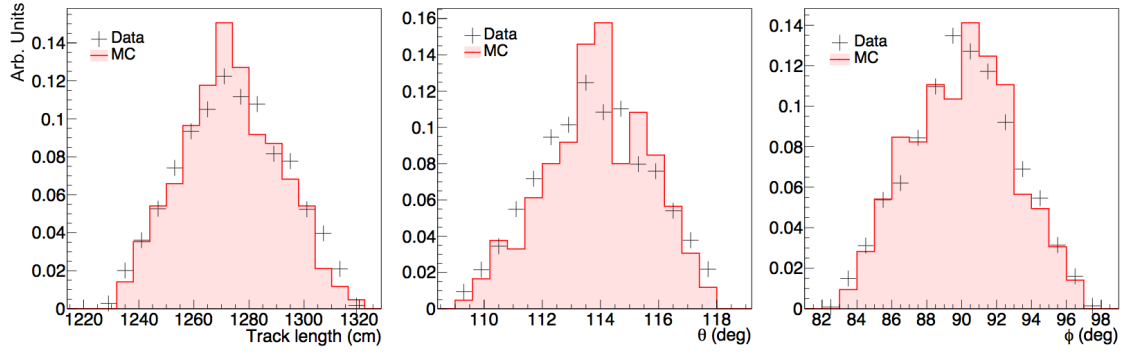


FIGURE 8.8: Normalized distributions of the track length between the CRT panels (left), the zenith angle (center), and the azimuthal angle (right), for the CRT-trigger data events in black and the CRTGen MC events in red.

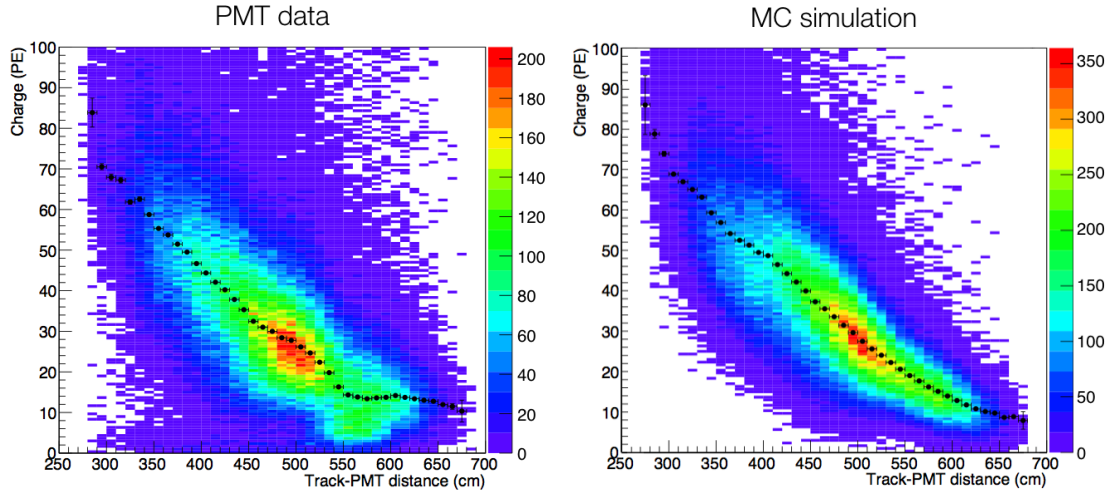


FIGURE 8.9: Collected S1 charge versus track-PMT distance for PEN PMTs: data (left) and MC sample (right). The color maps contain all the S1 signals detected by the PMTs and passing the event selection. A Gaussian fit of each charge-distribution every 10 cm is performed and the results (mean values) are plotted in black over the map. The vertical error bars correspond to the error from the fits and a 5-cm distance uncertainty (horizontal error bars) is included.

of events per bin. Each charge-distance correlation corresponds to the combination of several PMTs. Then, a Gaussian fit of the charge-distribution every 10 cm (vertical profiles of the 2D map) is performed to obtain the mean charge associated to each track-PMT distance.

A good agreement is observed up to ~ 5 m; beyond that distance, low-energy background (only present in data) prevails over the signal and the charge dependence with the distance is lost. The error of the mean parameter from the fit will be used as baseline charge error. In the data case, an additional systematic error of 4% (determined by varying the PMT gain) will be added in quadrature to the fit error of the charge in the next plots. On the other hand, the horizontal error bars correspond to an uncertainty of 5 cm, half of the considered distance-step in the maps.

Separate analyses for each WLS group are carried out because the charge range of interest for TPB PMTs (100-400 PE) does not overlap with the one for PEN (0-100 PE). The 30 PEN PMTs are combined in the analysis. Note that there are only 6 TPB PMTs and all of them are placed along a central line. The layout of TPB PMTs leads to features in the TPB charge-distance correlation that are independent of the WLS but prevent a correct interpretation of the results. In order to mitigate the correlation distortions, only 3 central TPB PMTs (FA0110, FA0132 and FA0139) that overlap in the same track-PMT distance range are considered in the analysis. The excluded TPB PMTs are rejected for being placed at the array border (FA0114 and FA0137; more affected by the light absorption on the cryostat and FC walls) or presenting a response below the expected one probably due to a smaller QE of its photocathode (FA0139).

8.3.4 Data-MC comparison

Figure 8.10 shows the charge-distance correlations obtained for data and simulation, and the corresponding data-MC ratios (see the fit results in Table 8.4). It is worth remarking the following aspects:

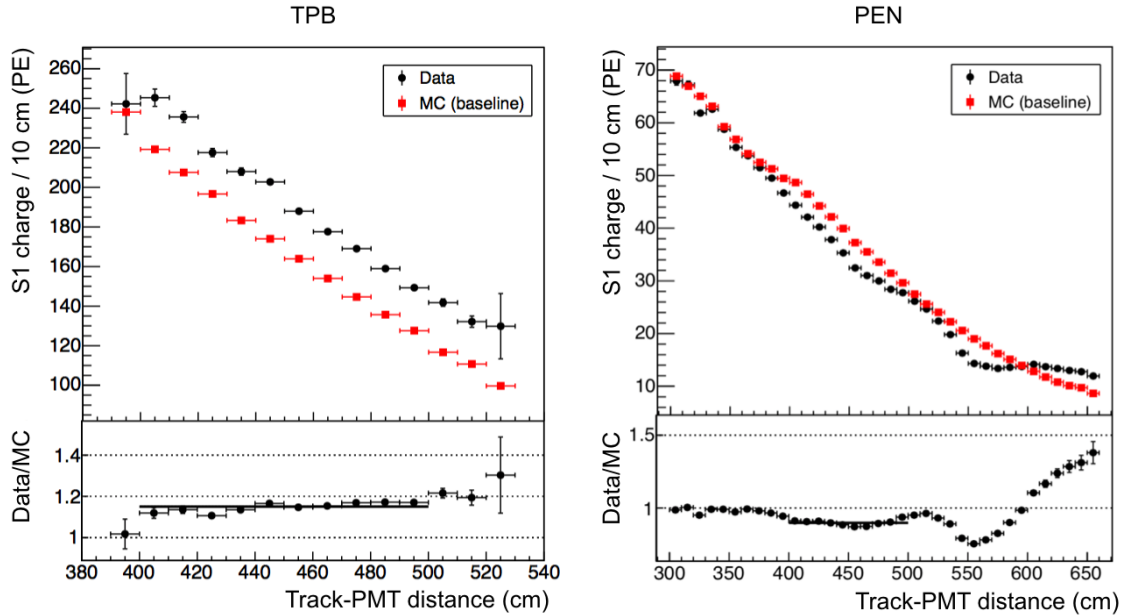


FIGURE 8.10: Data-MC comparison of CRT-trigger data and CRTGen MC samples, both for TPB (left) and PEN (right). Top panels: Average collected S1 charge as a function of track-PMT distance. Bottom panels: Ratio between the distributions of the top plots. A constant fit of each set is performed in 400-500 cm (see Table 8.4).

WLS	Data-MC charge ratio
TPB	1.150 ± 0.005
PEN	0.898 ± 0.005

TABLE 8.4: Charge ratios obtained from the fits to a constant shown in Figure 8.10.

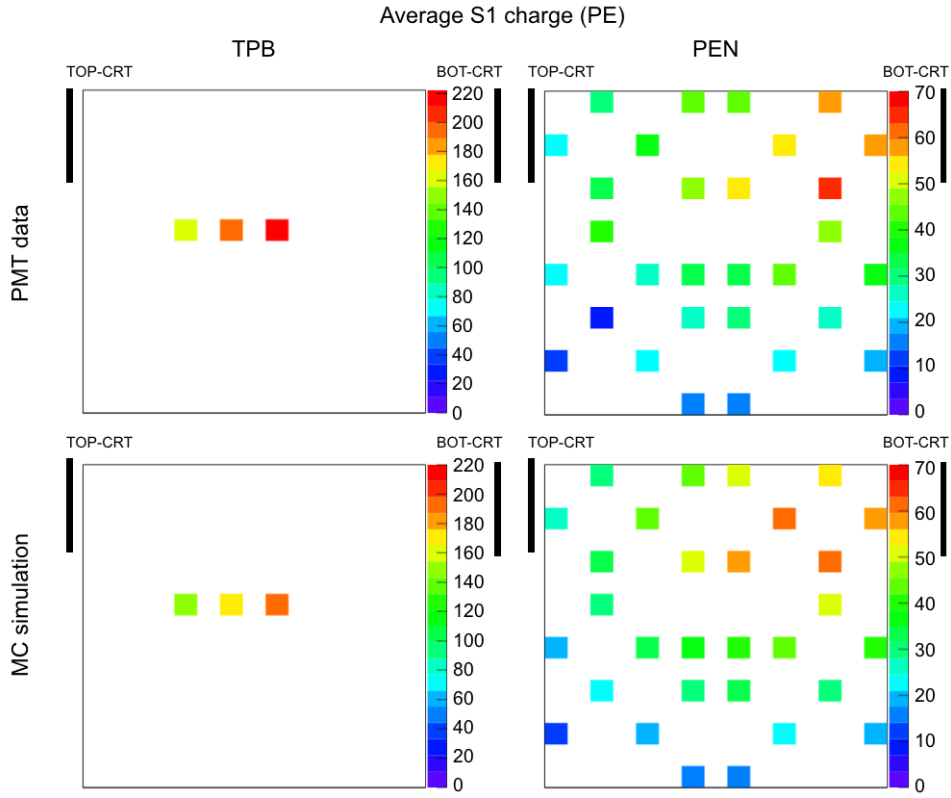


FIGURE 8.11: Average S1 charge per channel in CRT-trigger mode: top view of PMT array for data (top panels) and CRTGen-A MC sample (bottom panels). Both TPB (left) and PEN (right) results are presented. Each color square represents one PMT channel at its position in the detector. The approximate positions of the CRT frames are indicated with black rectangles.

- The TPB distributions are relatively smooth whereas the PEN ones are not. In the PEN case: 1) the MC correlation exhibits a slope change at ~ 400 cm related to the lack of detected signals at shorter track-PMT distances as it can be seen in Figure 8.9, 2) the data distribution starts to saturate at distances beyond ~ 500 cm. Beyond that point, the low-energy background (events that are not present in the simulation) prevails over the signals of interest and the light measurement is not reliable.
- The data-MC ratios are fitted to a constant in a particular track-distance range, 400-500 cm, in order to avoid the limitations described above. In the next analyses involving data and MC, the same distance interval is always studied.
- The data-MC ratios indicate that the simulation is validated within a 10-15% difference with data in the selected track-PMT distance range. The data-MC mismatch quantified here is a valuable input for further improvements of the TPB-PEN studies. Note that 100% efficiency of the TPB and the relative PEN-TPB efficiency from experimental measurements are assumed in the MC. More discussion on the PMT efficiencies will be given in Section 8.3.8

The top-view light detection maps (average S1 charge per optical channel) for the two WLS and both for data and baseline MC are presented in Figure 8.11. The approximate

CRT panel positions are indicated for an easier visual interpretation of the results. The obtained light detection patterns fairly reproduce the expected gradient: the PMTs which are closer to the bottom CRT (top right corner in the top view) detect more light than the rest. Besides, the gradient in the simulation is uniform and smooth across all the PMT array whereas in data some PMTs highlight with respect to their surroundings probably due to a gain deviation or a different QE.

8.3.5 Light yield suppression with drift field

The suppression of the electron-ion recombination process due to the drift field is investigated in this section. This phenomenon, already described in Section 2.5.1, implies the reduction of the primary scintillation light production and, hence, of the light detected by the PMTs. The field gradient along the height in ProtoDUNE-DP is a complex scenario that makes hardly feasible a complete understanding of the drift field effect over the light production. Even so, the light levels detected with the PDS at null drift field and at the maximum operating cathode HV (-50 kV) have been compared to roughly quantify such a light yield decrease. CRT-trigger data runs are employed in this analysis for two major reasons:

- According to some simulation-based estimations, at 1 m from the center of the active volume in the x - z plane (PMT plane) and with the cathode at -50 kV, the drift field is relatively uniform with a strength of about 0.170 kV/cm above the extender short circuit, but decreases until being null at the bottom of the active volume. Therefore, the CRT-trigger allows the selection of muons that, at least partially, always cross the highest field region (top half of the active volume), feature that can not be guaranteed with the any other PDS trigger mode.
- Given the non-uniform field pattern in ProtoDUNE-DP, the track reconstruction that the CRT-trigger mode provides is essential to estimate the effective field per muon track and so interpret the results.

Figure 8.12 shows the charge-distance distributions at the two cathode HVs and the corresponding ratios between them, both for TPB and PEN PMTs. It is remarkable the slope change that the PEN correlation exhibits at ~ 500 cm, indicating that, as commented before, at greater distances the PMT response is saturated by background signals of low-energy.

The collected charge (Q) versus the minimum approach distance (d) follows an exponential decay with a slope that contains various quenching effects:

$$Q(d) = \exp(-\lambda_{\text{Att}} \cdot d + C) \approx \exp(-[\lambda_{\text{Abs. LAr}} + \lambda_{\text{Abs. materials}} + \lambda_{\text{Rayleigh}} + \dots] \cdot d + C) \quad (8.5)$$

where the attenuation slope (λ_{Att}) is approximated to the sum of several decay constants. These components are associated to phenomena that contribute to the attenuation of the light during its propagation through the LAr bulk: absorption by LAr impurities ($\lambda_{\text{Abs. LAr}}$), absorption by detector materials ($\lambda_{\text{Abs. materials}}$), Rayleigh scattering that increases the light

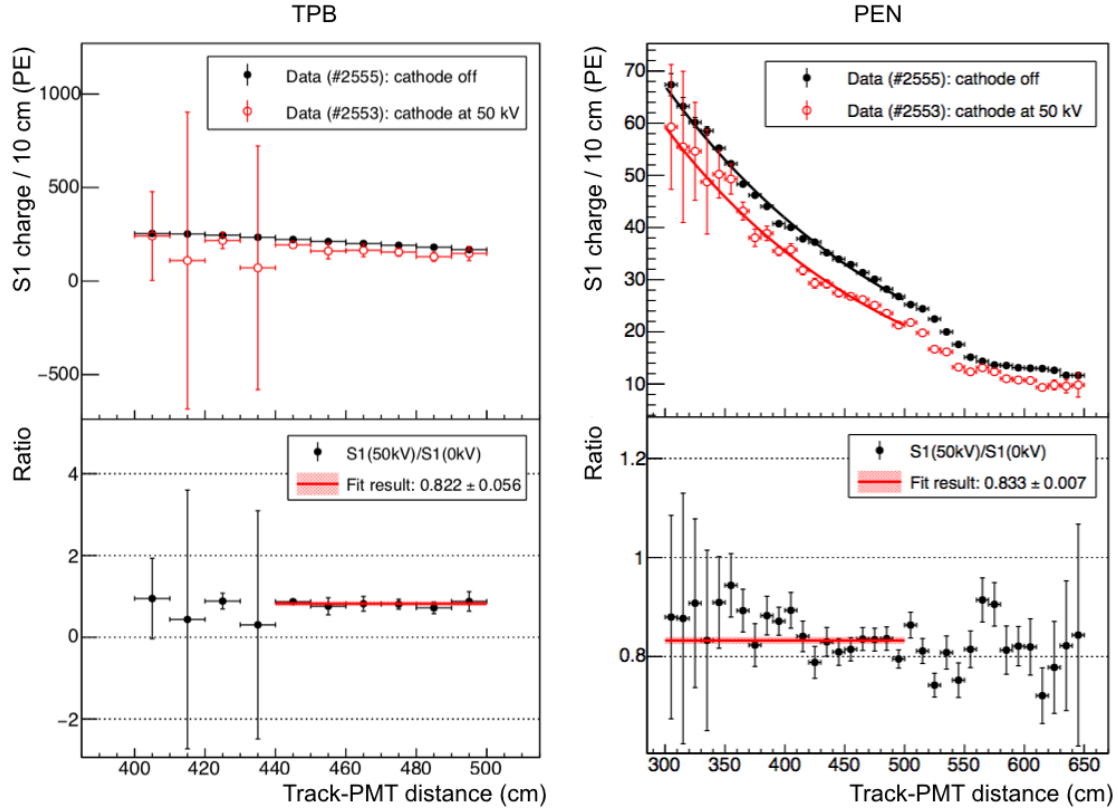


FIGURE 8.12: Top panels: Average collected S1 charge as a function of the track-PMT distance for TPB (left) and PEN PMTs (right) with null drift field (black) and with cathode at -50 kV (red). The larger error bars at short distance are due to the lack of statistics. In the case of PEN, each data sample is fitted to an exponential function; the fit is plotted as a solid line (values in Table 8.5). Bottom panels: Ratio between the S1 response with drift field and the one without. Each ratio distribution is fitted to a constant value (results in legends and in Table 8.5). The 440-500-cm and 300-500-cm ranges are respectively considered for TPB and PEN fits.

WLS	Cathode HV (kV)	Q-vs-d exp. fit $\exp(-\lambda_{\text{Att}} \cdot d + C)$ $1/\lambda_{\text{Att}}$ (cm)	$S1_{50\text{kV}}/S1_0$ charge ratio
TPB	0	—	0.822 ± 0.056
	-50	—	
PEN	0	212 ± 5	0.833 ± 0.007
	-50	195 ± 9	

TABLE 8.5: Parameters of the exponential and linear fits shown in Figure 8.12.

path making more likely the photon absorption ($\lambda_{\text{Rayleigh}}$), and others. The disentanglement of these correlated effects is not trivial but their impact in the overall attenuation will be assessed in the next sections.

In the distributions of Figure 8.12, the only expected change caused by the presence of the electric field is a variation of the initial light yield, *i.e.* a variation in the scintillation light production and not in its propagation or detection. In order to verify this, each PEN

charge-distance correlation is fitted to an exponential function as the one in Equation 8.5 and the results are included in Table 8.5. Given the saturation effect commented before, data in the 500-650-cm range are shown but ignored for the fits. Still, only PEN data are considered since the range to perform the fit is longer than in the TPB case, which is more limited by the statistics. The similar attenuation lengths obtained for the two data sets prove that the light propagation is not significantly affected by the drift field.

Concerning the ratios as a function of the track-PMT distance displayed in Figure 8.12, they are fitted to a constant to obtain the average ratio for each WLS group; see results in Table 8.5. In the case of TPB, the data at distances below 440 cm are ignored because some of the points have too large errors due to lack of statistics in the run with cathode on (1058 events versus 6730 events in the run with cathode off). The higher number of PEN PMTs mitigates this issue. The obtained results for TPB and PEN are compatible within errors. Thus, a weighted average ratio can be computed: 0.832 ± 0.008 , where the error corresponds to the sum in quadrature of the errors from the fits. The achieved value means that at least 17% of the scintillation light detected in absence of drift field comes from electron-ion recombination. The following aspects on the ratio results arise:

- The relatively constant ratio along the track-PMT distance range considered in the fits indicates that the light yield reduction is the same for all the CRT-trigger muon tracks. It means that the triggered muons are affected by a similar electric field and have similar track trajectories. It also points out that the drift field variation does not affect the light propagation. However, the significant uncertainty of the points at short track-PMT distances and the sensitivity limitation of the distant PMTs prevent from doing a more exhaustive investigation on the drift field impact with the distance.
- The non-dependency of the light suppression with the WLS confirms that the observed change with the drift field is neither related to the light detection.

An attempt to estimate the effective electric field along the CRT-trigger muon tracks has been done using the available 3D maps of the drift field in ProtoDUNE-DP from a COMSOL simulation corresponding to a cathode HV of -50 kV. Figure 8.13 includes examples of the field distribution in different planes of the active volume. The CRT-trigger muon beam crosses LAr regions with very different fields: from 0.20-0.30 kV/cm at the entry point for some tracks to 0-0.05 kV/cm at the exit point for others. The strong field gradient leads to a difficult evaluation of the drift field responsible for the light level reduction. Nevertheless, an approximation can be done as follows: for each valid track in data (muon candidate), the field value in the COMSOL simulation is checked at 100 equidistant points along the muon trajectory in the active volume (enough points given the 40-cm bin-width of the electric field maps); then, considering all the crossing muons, the average field value is computed. The distribution with all the field values considered is presented in Figure 8.14. The obtained effective field is $0.09^{+0.10}_{-0.02}$ kV/cm, where the errors are the RMS of the values below and above the mean value.

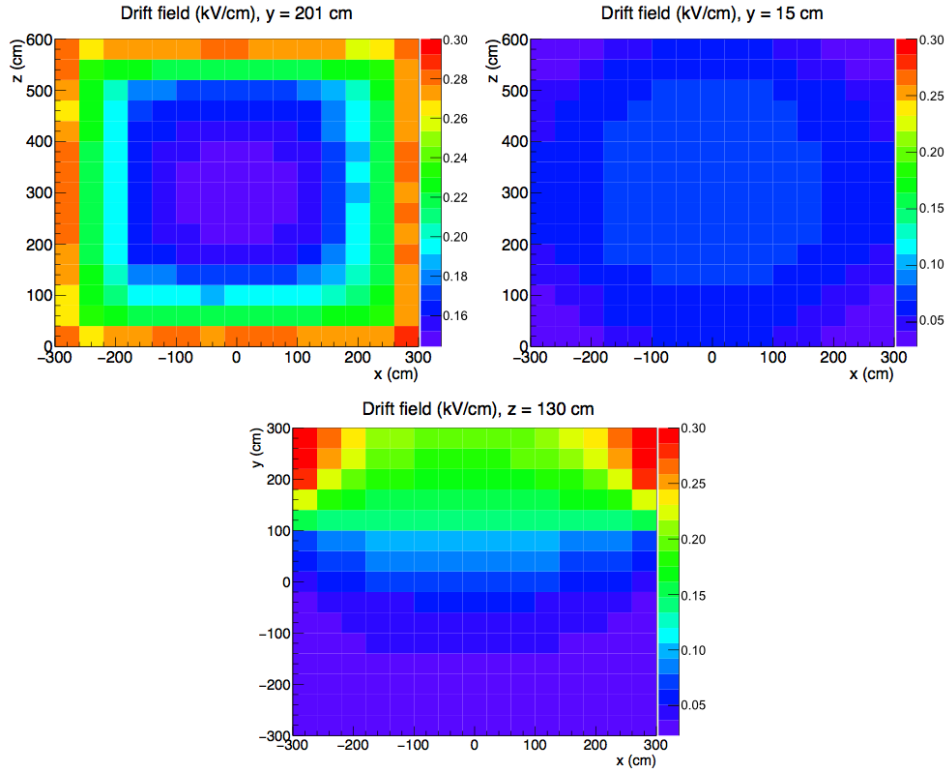


FIGURE 8.13: Maps of the drift field in ProtoDUNE-DP with cathode at -50 kV (COMSOL simulation) used to calculate the average field value per CRT-trigger muon track. Three particular planes of the active volume are shown. The drift direction is along the y-axis and the color scale is the electric field strength.

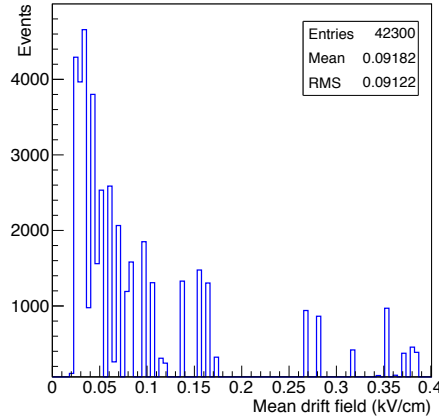


FIGURE 8.14: Distribution of the drift field values along the CRT-trigger muon tracks (obtained from the simulation in COMSOL).

The field approximation above is associated to the light-yield ratio previously discussed. In order to verify that the ratio-field result follows the expected trend (empirical Birks' law), the value is displayed in Figure 8.15 together with some ratios reported in the literature. Despite the relatively large uncertainty of the ProtoDUNE-DP result, a fair agreement is found with previous works. It is remarkable that the plot contains results

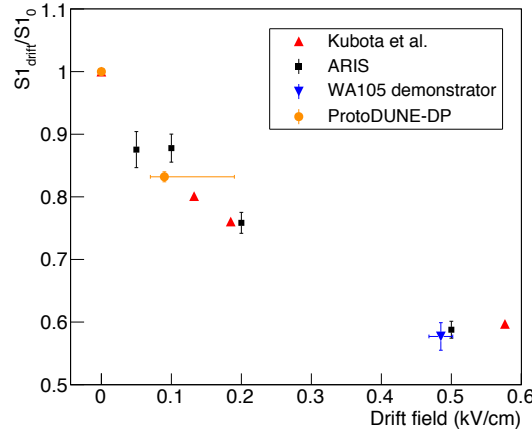


FIGURE 8.15: Light yield reduction with drift field measured by different experiments (red triangles from [92], black squares from [188], blue inverted triangles from [85]), including the ProtoDUNE-DP result (orange circles) discussed in this section.

from both ground-level cosmic muons (WA105 [85]) and MeV-electrons (Kubota *et al.* [92] and ARIS [188]), being the latter more comparable to ProtoDUNE-DP in terms of drift field. In conclusion, the electric field affects similarly to both particles in LAr from the recombination point of view.

8.3.6 Study of the Rayleigh scattering length

The size of ProtoDUNE-DP, the longest drift-distance LArTPC ever operated, allows an unprecedented study of parameters that play a role in the light propagation in LAr such as the Rayleigh scattering length (RSL). In this section, an estimation of the RSL value is carried out by comparing the measured light signals with the light predicted by the MC simulation where this length is a tunable parameter. The two tested RSL in the MC are 61 cm and 99.9 cm. The former length hypothesis is based on the results reported in [101], [102] and [96], whereas the latter is driven by a more recent experimental measurement presented in [77]. The light attenuation modelling with an exponential function in the distance parameter (Equation 8.5) is also exploited here to extract information. This approach provides a measurement of the overall attenuation in data and MC, and so the agreement for the different simulated configurations can be evaluated.

In Figure 8.16, each charge-distance correlation under study is fitted to an exponential (upper plots) with results in Table 8.6; the data-MC ratios for the two simulations are also presented (bottom plots). The track-PMT distance range studied is 400-500 cm due to the statistics and saturation limitations explained before and to focus on the further distances where the sensitivity to the RSL effect is higher. It has to be noted that the goal of this study relies on the distribution shape and not on the total light amount which can be adjusted through the PMT efficiency parameter. Thus, the RSL used in the MC is not considered the cause of the observed data-MC mismatch. The attenuation length values

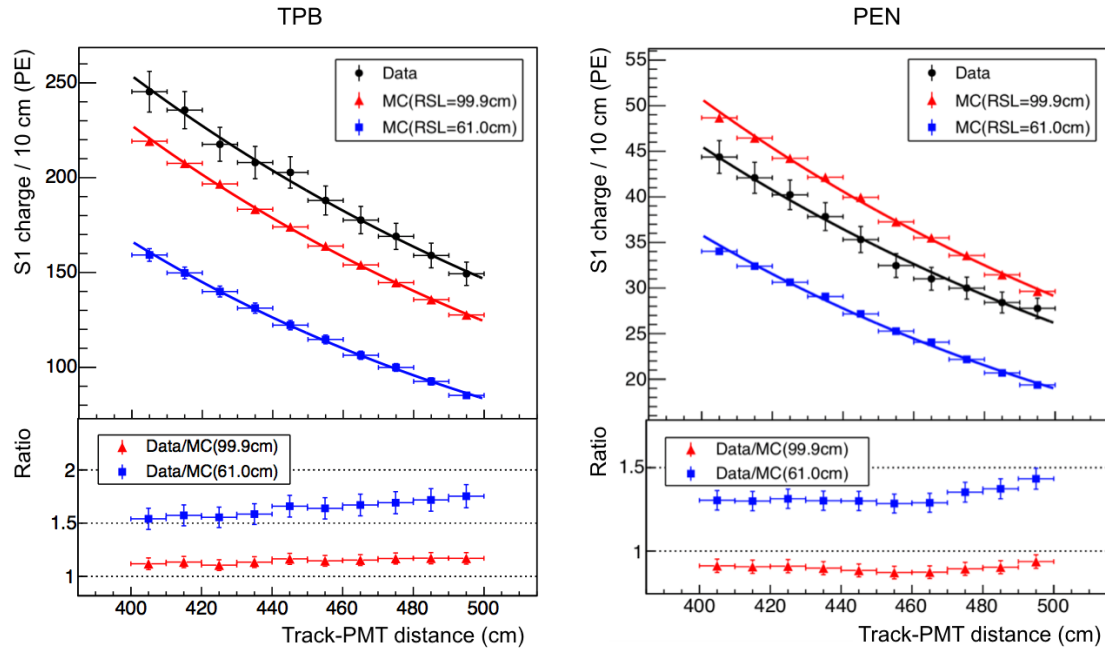


FIGURE 8.16: Top panels: Average collected S1 charge as a function of the track-PMT distance for TPB (left) and PEN PMTs (right). Two MC samples with different Rayleigh scattering length values (61 cm and 99.9 cm) are compared to data. For each data and MC sample, an exponential fit is performed and plotted as a solid line (results in Table 8.6). Bottom panels: Data-MC ratio for the two previous MC samples.

WLS	Sample	RSL (cm)	$1/\lambda_{\text{Att}}$ (cm)
TPB	Data	–	182 ± 18
	MC	99.9	165 ± 9
		61	145 ± 9
PEN	Data	–	180 ± 17
	MC	99.9	180 ± 10
		61	157 ± 9

TABLE 8.6: Attenuation lengths from the exponential fits shown in Figure 8.16.

and the more-constant data-MC ratio point out that the agreement between data and the 99.9-cm MC sample is better than with the 61-cm value.

As the measured attenuation length is higher than the preferred RSL, the light is expected to undergo Rayleigh scattering before being deeply attenuated due to, for example, absorption by LAr impurities or detector elements. This relatively long light path before a significant light quenching or absorption is achieved in ProtoDUNE-DP thanks to the excellent LAr purity and the large free LAr volume.

WLS	MC(full-absorption)/MC(baseline) charge ratio
TPB	0.920 ± 0.014
PEN	0.889 ± 0.006

TABLE 8.7: Charge ratios (fits to a constant) between the charge-distance MC correlations considering full absorption (0% reflectance) and 26% of reflectance for VUV light in FC, cryostat walls, cathode and ground grid.

8.3.7 Impact of the reflected VUV light

As explained in Section 7.3.2.1, the reflectivity for VUV light in the FC (aluminum), and in the cryostat walls, cathode and ground grid (made of stainless steel) is set to 26% in the baseline MC sample at the light propagation step (Geant4 tracking). The other detector elements are simulated to be fully absorptive, so any photon reaching their surfaces is removed from the simulation. It is important to point out that the material reflectivity can strongly vary from one manufacturer to another and, hence, an improvement in the MC would be the use of the particular reflectances of ProtoDUNE-DP materials. Besides, additional reflected light sources both for VUV (implementing the reflectivity of other materials like the CRP extraction grid made of stainless steel) and visible light (from the WLS re-emission, not included in the current simulation) could be added to the simulation. While a VUV reflectance of 26% is considered for aluminum (according to measurements [178]), the same VUV reflectance is assumed in stainless steel surfaces as no measurements were found. Therefore, further investigation of the material reflectivity for VUV photons is critical for the complete understanding of the light propagation in a LAr detector.

A test photon library where all the components have null reflectivity is compared to the baseline in order to evaluate the impact of the VUV-photon reflections on the collected light by the PDS. The ratio between the two charge distributions versus the track-PMT distance is obtained and fitted to a constant as in the previous sections. Results are presented in Table 8.7. It is retrieved that about 8% and 11% of the light respectively detected by TPB and PEN PMTs in the baseline MC corresponds to VUV-light reflected on the FC, cryostat walls, cathode and ground grid. The separate study of the reflections per component is not considered relevant here given the small difference found between the two reflectivity scenarios along the track-PMT distance range.

8.3.8 PMT efficiency analysis

The data-MC ratios already presented in Table 8.4 indicate that the charge collected by TPB-coated PMTs in the simulation is about 15% above data charge whereas the one detected by PEN-foil PMTs is about 10% below the measured value. The underestimation in the TPB simulation can be explained as not all the reflected light is simulated, nor the background sources. On the other hand, the overestimation in the PEN case can be attributed to the PEN efficiency determination.

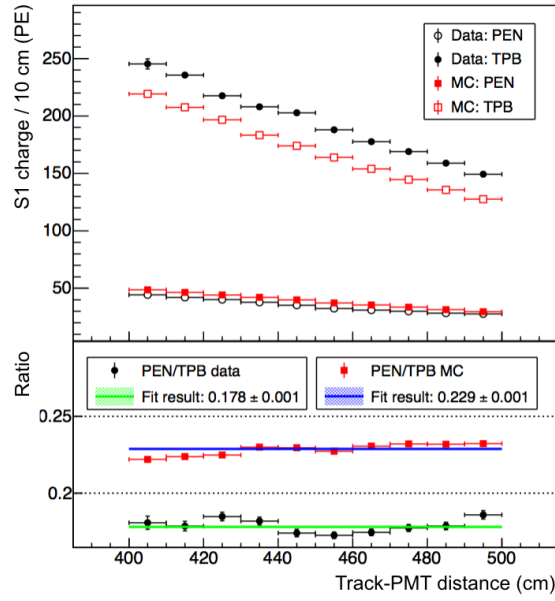


FIGURE 8.17: PEN-TPB charge ratio obtained in the track-PMT distance range of interest and fitted to a constant (result included in the legend).

Regarding the relative PEN-TPB performance, Figure 8.17 shows the PEN-TPB charge ratios obtained from CRT-trigger data and MC as a function of the track-PMT distance. A common distance range for both WLS (400-500 cm) is studied. The results of fitting each PEN-TPB ratio distribution to a constant are 0.178 ± 0.001 and 0.229 ± 0.001 for data and simulation, respectively, as shown in the legends. Therefore, the observed PEN-TPB relative response in data is $\sim 22\%$ lower than the obtained from simulation. It is important to remark that these PEN-TPB ratios from ProtoDUNE-DP light data and MC represent novel measurements on the relative PEN performance in a large-scale LAr detector and are valuable inputs for future PEN-TPB analyses.

8.4 Analysis of the comic muon detection

The rate of cosmic particles crossing ProtoDUNE-DP is large because of its location at surface. As a consequence, the detector represents a perfect test-bench to study the PDS capability for detecting muons and providing calorimetric information. Results of interest arise from the light data analysis itself but also from the comparison with the light simulation. While in the previous section the focus was on the light mechanisms in LAr along with the validation of the light simulation, here the goal is to determine the cosmic muon rate and the overall detection efficiency of the PDS in order to extract useful and quantitative information towards future light detection systems in giant LAr TPCs.

First, the data sets and MC samples under study are described in Section 8.4.1. Then, the algorithm to identify S1 signals in the PMT waveforms is explained in Section 8.4.2 along with the S1 signal characterization in amplitude and charge. The results on the

S1 rate are summarized in Section 8.4.3 and the cosmic muon flux measurement is discussed in Section 8.4.4. Finally, in Section 8.4.5, the observed light yield from muons is investigated for the two WLS methods.

8.4.1 Random-trigger: runs of interest and MC samples

The studies on the S1 signal presented so far (in previous chapters and before in this one) correspond to light events taken either in PMT-trigger or CRT-trigger modes, whereas the results shown in the following are based on S1 signals from light data acquired in random-trigger mode. These data comprise more varied signals as the light reaching the PMTs can be generated at any point of the LAr volume and be associated to very different track topologies and energies. With random trigger, some cosmic muons cross the LAr bulk close to the PMT array at the bottom while others produce light in the most distant region at the top part of the detector.

In total, five data runs acquired along seven months (October 2019 - April 2020) with random trigger are analyzed and compared with the baseline CORSIKA-based simulation which aims at reproducing the PDS response to the total cosmic-ray exposure. The cosmic-muon data sample allows the validation of the PDS simulation to demonstrate that the detector response is correctly modeled and understood. In addition to the random-trigger

Sample	#Sets	PMT gain ($\times 10^7$)	Analyzed time per set* (ms)	Comment
Data	2	1	1053	Oct. 2019
	3	5	956	Feb., Mar., Apr. 2020
MC	1	5	960	Baseline
	2			$\pm 10\%$ PMT efficiency

TABLE 8.8: Random-trigger PMT runs and CORSIKA-based MC simulation samples for the S1 signal studies. While the PMT efficiencies in the baseline MC are $E_{TPB}=0.090$ and $E_{PEN}=0.016$, the test efficiencies ($\pm 10\%$) are $E_{TPB}=0.081, 0.099$ and $E_{PEN}=0.014, 0.018$. * Total time of PMT waveform considered in this analysis.

Particle type	#Events	#Events per ms	Fraction (%)
Muon($\pm$)	86620	90	56.9
Neutron	36193	38	23.8
Gamma	17227	18	11.3
Electron, positron	8194	9	5.4
Proton	3854	4	2.5
Others (pions, anti-p, anti-n)	32	<1	<0.1%
Total	152120	160	100.0

TABLE 8.9: Particle content of the simulated cascades originated by cosmic rays over ProtoDUNE-DP (CORSIKA-based MC sample). The time of exposure considered is 960 ms.

analysis, CRT-trigger data are also analyzed to evaluate the detected light yield for different muon samples.

The particular data-taking conditions and some simulation parameters can be seen in Table 8.8. The simulation has been performed following the steps explained in Section 7.3 with the baseline configuration although 2 additional MC samples are employed to determine the impact of the effective PMT efficiency on the muon flux result. The content of the particle showers generated with CORSIKA can be seen in Table 8.9. As expected, muons are the major particle component ($\sim 57\%$).

8.4.2 S1 signal characterization

The main drawback of the random trigger is the S1 signal identification, as it is not aligned with the trigger. Therefore, the development of an effective S1 signal finding algorithm is crucial. In addition, a good understanding of the detected S1 signals is fundamental and must include the analysis of some basic features. Namely, amplitude and charge per optical channel are studied here.

8.4.2.1 S1 signal identification

The S1 signals are identified in the PMT waveforms using a custom peak-finding algorithm which takes into account the following aspects:

- Any pulse in the waveform with an amplitude larger than the maximum expected SPE amplitude at 2σ is considered a potential S1 signal. The amplitude threshold is based on the results of the average SPE amplitude and its spread as functions of the PMT gain presented in Section 8.2.2. In fact, a custom threshold is set for each PMT gain according to the closest calibration. The lack of an intermediate component in the simulated scintillation time profile (see Chapter 7) results in a different charge-amplitude correlation than in data and, hence, a correction over the amplitude is applied in the MC analysis in order to select events that correspond to the same deposited energy than in data. More details on this correction will be given in the next section.
- When a potential S1 signal is found, a veto time window of variable length is applied after the position of the maximum signal amplitude. Each ignored window lasts until a non-stop time of $4.8 \mu\text{s}$ (300 samples at 16-ns sampling) without any potential S1 signal is achieved. Hence, the minimum veto time per S1 signal is $4.8 \mu\text{s}$ but, if a potential S1 signal is detected during that time, a new $4.8\text{-}\mu\text{s}$ veto window beginning at that point is considered, and so on and so forth. In this way, no spurious S1 signals are counted during the tail of the slow scintillation light component. The goal is to find a compromise between the proper baseline recovery before resuming the counting and the minimum veto time for a correct rate estimation.

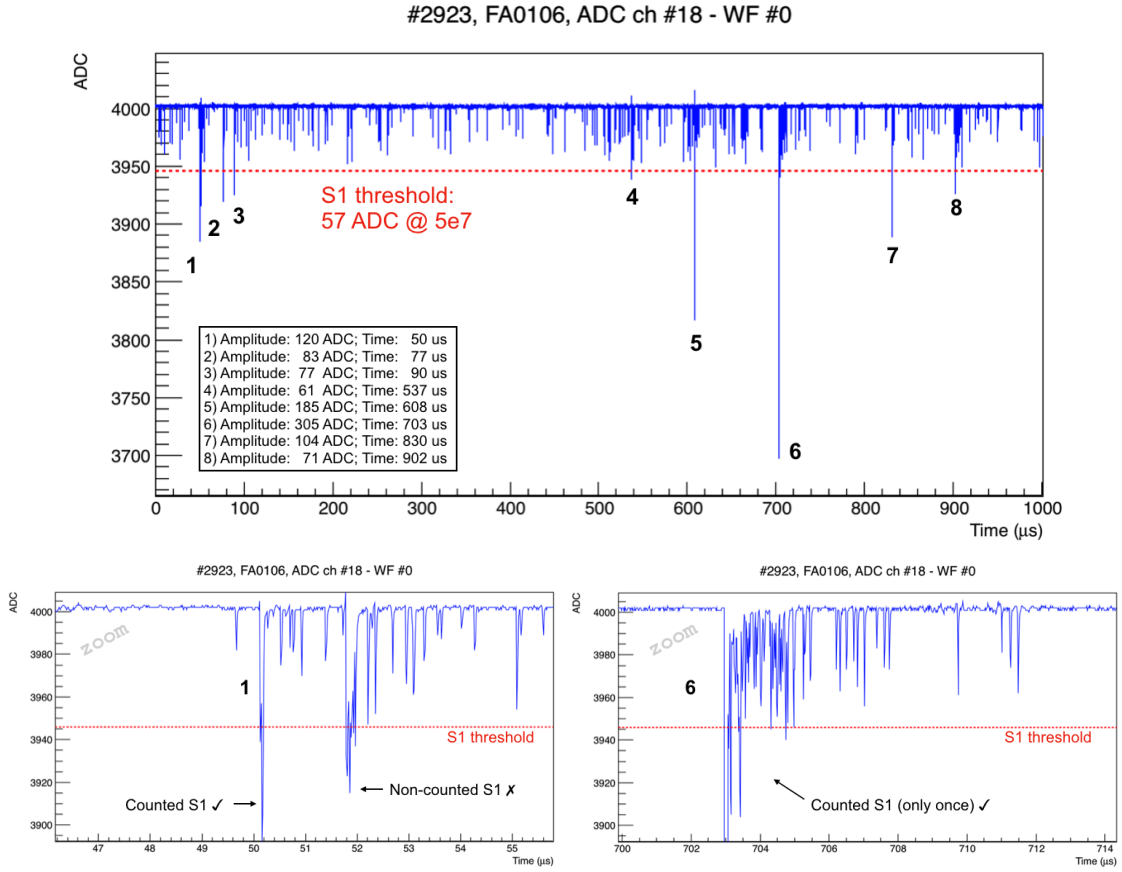


FIGURE 8.18: Example of S1 signals identified in a PMT waveform from a random-trigger data run. The top panel corresponds to the complete event (1-ms window) and the bottom panels are zooms of parts of the waveform where a potential S1 signal is missed in the counting (left) and where a correct identification is achieved (right).

- An optical reconstruction to reject small and uncorrelated signals is performed by searching coincidences among PMTs. A coincidence is given when at least 2 PMTs detect the potential S1 signal within a coincidence interval of 112 ns. The coincidence interval is defined taking into account that, although the relative time accuracy on the S1 detection among the PMTs is better than 16 ns [190], the time position of the maximum amplitude can oscillate from one PMT to another up to 112 ns due to an ADC limitation. The coincidence requirement is applied as follows:
 1. One PMT is selected as reference and, for each S1 signal detected by this PMT, the records of the other PMTs are checked and the number of coincidences for each signal is added to the information (*i.e.*, time, amplitude, charge and number of coincidences).
 2. A S1-coincidence is given when the reference PMT plus another PMT detect a S1 signal within a coincidence interval of 112 ns (± 3 samples with respect to the detection time of the reference PMT). Then, it is assumed that the S1 signals were originated by the same crossing muon.

3. In order to have a result that is not dependent on the reference PMT, the 36 PMTs are analyzed as reference and the average for each WLS group is obtained: 6 and 30 PMTs of reference are considered for TPB and PEN, respectively. Note that when a TPB PMT is taken as reference, the coincidences can be with any other PMT (either TPB or PEN), and the same in the case of a reference PMT with PEN.

An example of PMT waveform from a random-trigger data run is displayed in Figure 8.18. The different potential S1 signals that are identified with the method are indicated. The bottom plots in the figure show a potential S1 signal which is not counted for being too close to another one (left plot) and a good S1 identification where the signal is counted only once even though the threshold is crossed during the slow component of the signal (right plot).

8.4.2.2 S1 amplitude and charge

The amplitude (maximum around the fast component) and integrated charge in $4 \mu\text{s}$ (Q_{total} component defined in Section 6.3.2) of the S1 signals collected by each PMT are studied here. Only full-range PMTs are considered (see Section 6.3.4).

As mentioned before, the simulated scintillation light profile leads to a charge-amplitude correlation in the MC that does not agree with the observed trend in data. To illustrate this, the initial amplitude-charge distributions for a TPB PMT are presented in Figure 8.19 top-left. Since there is no intermediate component in the simulation, larger signal amplitudes are associated in the MC to the same integrated S1 charge than in data. The light-profile difference is critical in the identification of S1 signals along PMT waveforms as the method is based on an amplitude threshold. As a consequence, the threshold must be adjusted in the MC in order to select events in the same charge range than in data. Each charge-amplitude correlation is linearly fitted (blue lines) and the data-MC ratio between the slopes of the distributions gives a factor that allows a fair comparison, as shown in Figure 8.19 top-right, where the amplitude is scaled by this factor. The average correction factor obtained from the data runs under study and the CORSIKA-based sample is 2.17 ± 0.08 , being the error the STD among PMTs. Based on this result, common for the two WLS methods, the amplitude threshold in the simulation analysis is set at the expected SPE amplitude plus 2σ but scaled by 2.17. For example, at a gain of $5 \cdot 10^7$, the S1 threshold is 55 ADC counts for data and 120 ADC counts for MC, respectively.

However, it can be seen in Figure 8.19 top-right that the ADC saturation cut at 4096 ADC counts (ADC limit) is not valid for simulation. Larger signal amplitudes can be recorded leading to the same integrated charge as no ADC saturation effect is implemented. Thus, the ADC limit in the simulation is adjusted as the threshold, that is, scaled by the aforementioned factor, resulting in 8888 ADC counts. Thanks to this correction, compatible data and MC event sets are obtained, see Figure 8.19 bottom.

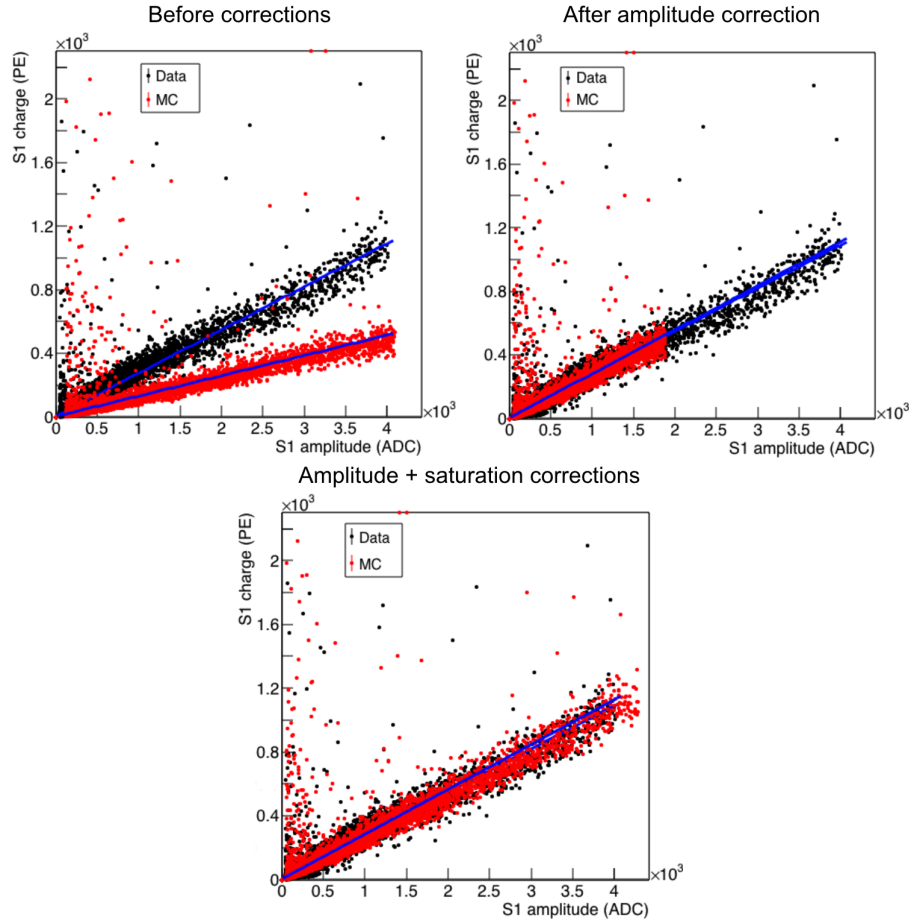


FIGURE 8.19: S1 charge-amplitude distributions for a TPB PMT (FA0110) before corrections (top-left), after scaling the MC amplitude by 2.17 (top-right) and after also adjusting the ADC saturation limit in MC by 2.17 (bottom).

The data distribution of detected S1 charge per PMT is fitted with a Landau function in order to obtain the most probable value (*MPV*) and width (σ) parameters, which are shown in Table 8.10. The good agreement among data taken throughout seven months (small dispersion among data sets shown in the table) indicates the stable performance of the WLS during the detector operation. In other words, no significant deterioration of the TPB coating is observed in this analysis. A constant response with time is also achieved in the PEN case. Table 8.11 contains the *MPV*, for data and also for MC with and without the amplitude corrections that modify the threshold and the saturation limit. According to the results, the corrections improve the data-MC agreement in charge for TPB PMTs but the discrepancy after corrections is similar to the mismatch observed with no corrections in the case of PEN. As discussed in Section 8.3.8, the relative PEN-TPB response in the MC (which determines the assumed PEN efficiency) seems to be $\sim 22\%$ overestimated with respect to data. Thus, the charge excess obtained here for PEN once the corrections are applied is attributed to this known uncertainty in the simulated PEN efficiency.

WLS	S1 charge per PMT (PE)	
	$MPV \pm \sigma$	ΔMPV with time*
TPB	22±9	0.5
PEN	16±7	0.4

TABLE 8.10: S1 charge ($MPV \pm \sigma$) per PMT from random-trigger data for TPB and PEN PMTs.
* ΔMPV with time: STD among results from data sets taken along seven months.

WLS	S1 charge per PMT (PE)		
	Data	MC with	MC without
TPB	22	24	14
PEN	16	22	12

TABLE 8.11: S1 charge (MPV) per PMT in random-trigger mode, for data and also for MC with and without amplitude corrections.

8.4.3 S1 rate per PMT

The rate of S1 signals detected by each PMT is computed as the number of identified S1 signals ($\#S1_{coinc}$, detected in coincidence by at least 2 PMTs) divided by the total waveform time ($time_{total}$) that is analyzed:

$$S1 \text{ rate} = \frac{\#S1_{coinc}}{time_{total}} \quad (8.6)$$

It has to be noted that the obtained S1 rate is not the overall cosmic muon rate in the detector but the average muon rate per optical channel. Results on the S1 rate per PMT are presented in Table 8.12 and they point out an excess of simulated S1 signals induced by muons: around 16% (11%) higher S1 rates are detected by the TPB (PEN) PMTs in simulation than in data. Nevertheless, the muon flux with the model chosen within CORSIKA to generate the primary cosmic particles, the CMC model, is expected to be up to 20% above the one obtained with a model assuming only cosmic protons, as reported in [191], and it can be up to 25% lower for other particle generators. Thus, the observed data-MC deviation is within the discrepancy between the MC models.

For the selected data runs, the S1 rate variation throughout seven months is small according to the rate stability with time displayed in Figure 8.20 or in Table 8.12 (2-5%). Furthermore, no dependency on the PMT gain is found, indicating that the amplitude threshold is correctly defined in the S1 identification. The S1 rate is constant within the same data sample (<1% of variation). These results confirm the stable performance of the system, already observed in terms of charge detection.

In Figure 8.21, the maps with the S1 rate per optical channel are presented for both data and MC. On the one hand, the detected rate per channel is quite uniform across the PMT array for each WLS group (within a 10% difference) except for one PEN PMT

WLS	S1 rate per PMT (kHz)		Data-MC ratio
	Data	MC	
TPB	$8.8 \pm 0.5 (\pm 0.2)$	10.2 ± 0.5	0.86 ± 0.09
PEN	$5.5 \pm 0.6 (\pm 0.3)$	6.1 ± 0.4	0.90 ± 0.10

TABLE 8.12: Average S1 rate per PMT in random-trigger mode and data-MC ratios. The average of 5 data runs is shown. The errors in the S1 rate correspond to the STD among PMTs; errors between brackets (only in data) are the dispersion among the 5 data sets.

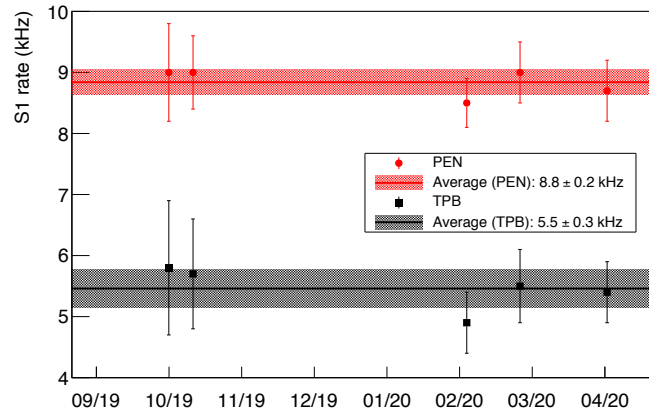


FIGURE 8.20: Stability with time of the S1 rate per PMT: PEN-foil PMTs in red and TPB-coated PMTs in black. The average value per data set is displayed and the vertical error bars correspond to the dispersion among PMTs (STD). The color bands show the average value and spread throughout seven months.

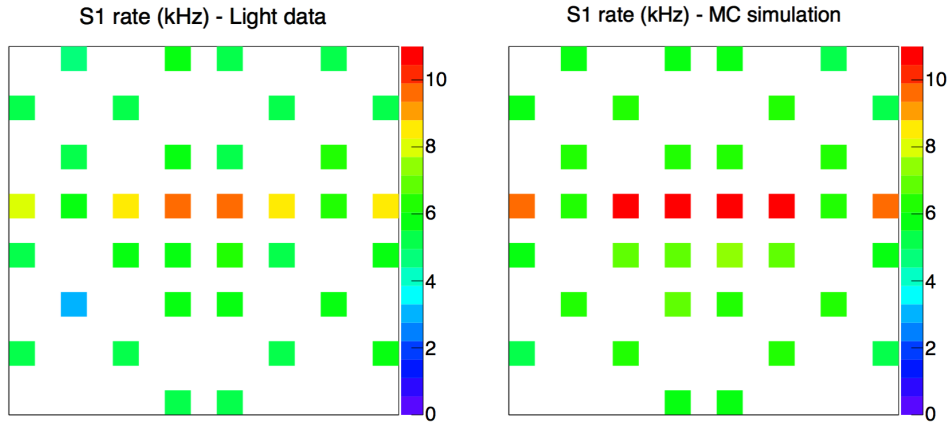


FIGURE 8.21: S1 rate per optical channel in random-trigger mode: top view of distributions in the PMT array for data (left panel, average of 5 runs) and simulation (right panel). Each color square represents one PMT channel at its position in the detector.

(channel #5 in Figure 4.8) in data that exhibits a deviation of $\sim 46\%$ with respect to the average PEN response. This difference can be attributed to a lower QE which is an intrinsic property of each individual PMT. On the other hand, it is observed that the central TPB PMTs detect more signals than the others, both in data and simulation. This was expected

as they subtend a larger solid angle of LAr volume and they have a higher number of adjacent PMTs to detect in coincidence with them. In particular, the detection by the 2 (4) central PMTs is enhanced in data (MC) with respect to the more outer PMTs.

8.4.3.1 Impact of the S1-coincidence requirement

The average S1 rate per WLS is displayed in Figure 8.22 as a function of the minimum required number of PMTs detecting the S1 signal in coincidence. In general, the S1 rate is higher in MC than in data for any minimum number of PMTs detecting in coincidence. It can be observed that the S1 rate drops significantly from a threshold of a single detecting PMT (zero or more coincidences) to at least 2 detecting PMTs (one or more coincidences), especially for data. The uncorrelated rate of S1 signals can be computed as:

$$\begin{aligned} \text{Uncorrelated S1rate} &= \text{S1rate}(\geq 1 \text{ PMT}) - \text{S1rate}(\geq 2 \text{ PMTs}) = \\ &= \text{S1rate}(\geq 0 \text{ coincidences}) - \text{S1rate}(\geq 1 \text{ coincidences}) = \text{total S1rate} - \text{correlated S1rate} \end{aligned} \quad (8.7)$$

where the correlated S1 rate corresponds to the baseline S1 identification method (results already presented in Table 8.12).

The total and uncorrelated S1 rates are contained in Table 8.13. The fraction of non-correlated signals in data is remarkable and, hence, the coincidence cut rejects significantly more potential S1 signals of low energy in data (30-47%) than in MC (7-9%). This was expected because the simulation only includes cosmic-ray activity and no low-energy backgrounds are considered. In particular, the backgrounds in the data sample described in Section 8.2.1 can originate signals beyond the SPE level and contribute as small S1

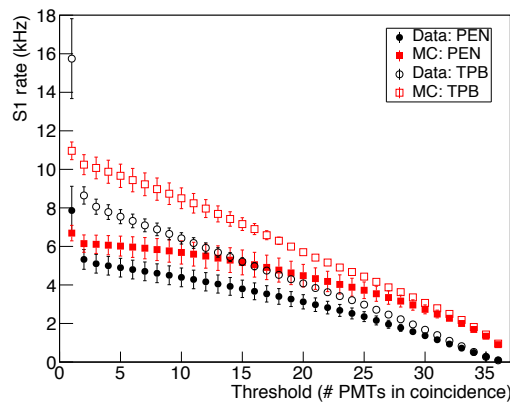


FIGURE 8.22: Average S1 rate vs. minimum number of PMTs detecting in coincidence for each WLS group, for data (in black) and MC simulation (in red). The vertical error bars are the STD among results taking different PMTs as reference. A single data set is displayed here, albeit no significant differences with other runs are found.

WLS	Sample	Uncorrelated S1 rate (kHz)	Total S1 rate (kHz)	Uncorrelated/total (%)
TPB	Data	7.7 ± 3.3	16.5 ± 2.8	47
	MC	0.8 ± 1.0	11.0 ± 0.5	7
PEN	Data	2.4 ± 2.9	7.9 ± 2.3	30
	MC	0.6 ± 0.8	6.7 ± 0.4	9

TABLE 8.13: Average rates of S1 uncorrelated signals (no coincidences) and all S1 signals (at least one PMT detecting the signal), and fraction of the uncorrelated signals over the total detected light. The errors correspond to the spread among PMTs (STD).

signals to the total rate. This kind of interactions are expected to deposit energy very locally in space, which explains the cancellation of such events when requiring that at least 2 PMTs detect the light.

8.4.4 Measurement of the cosmic muon flux

The cosmic muon flux can be computed as the simulated muon flux scaled by the measured S1 rate data-MC ratio. Considering the surface covered by the PMT array ($\sim 36 \text{ m}^2$) and the fraction of muons crossing such an effective area in the MC, the atmospheric muon flux at the Earth's surface predicted by CORSIKA is 166 Hz/m^2 . Then, the predicted flux is scaled by the ratios between the data and MC rates given in Table 8.12.

The flux result is the weighted average of both TPB and PEN results. The systematic uncertainty on the flux is estimated by varying the amplitude threshold in the S1 identification by $\pm 3\%$ (equivalent to ± 2 ADC in data and ± 4 ADC in MC) and the PMT efficiency in the MC by $\pm 10\%$ (see test efficiencies in Table 8.8). The threshold variation is motivated by the dispersion in the correction factor 2.17, which is ± 0.08 (3%). On the other hand, the PMT efficiency variation comes from the observed $\sim 10\%$ of data-MC deviation previously reported for the S1 rates. The individual uncertainty contributions are displayed in Table 8.14. In this way, a cosmic muon flux of $148^{+7}_{-11} \text{ Hz/m}^2$ is measured in ProtoDUNE-DP at CERN, at 455 m altitude above mean sea level. The ProtoDUNE- DP

Systematic variation	Uncertainty (%)
+3% amplitude thresholds	-3.2
-3% amplitude thresholds	-5.2
+10% PMT efficiency in MC	-4.2
-10% PMT efficiency in MC	+4.9
Total	+4.7 / -7.4

TABLE 8.14: Systematic uncertainties on the cosmic muon flux result.

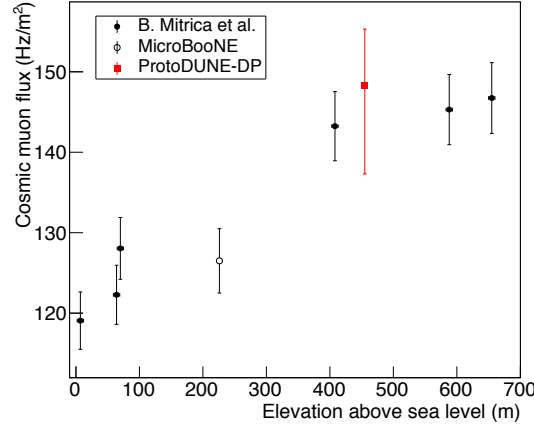


FIGURE 8.23: Cosmic muon flux determined in ProtoDUNE-DP at CERN at 455 m above the mean sea level (red square) compared to the measurements reported in [191] (empty black dots) and [192] (filled black dots).

cosmic muon flux result is found to be consistent with other measurements at ground-level given in the literature, as it can be seen in Figure 8.23.

8.4.5 Observed light yield from cosmic muons

The observed light yield by the PDS for muon interactions is investigated considering the use of the system as a calorimeter. Taking into account all the cosmic muon tracks across the LAr volume, the average deposited energy per muon is determined with the CORSIKA cosmic-ray simulation to be 813 MeV (Figure 8.24). Then, the observed light yield in random trigger is calculated as the total S1 charge collected by all PMTs divided by the average deposited energy per muon. The results can be seen in Table 8.15. This approach

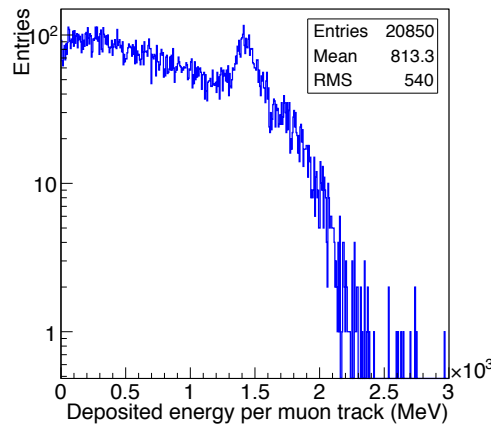


FIGURE 8.24: Deposited energy in the LAr bulk per muon track crossing the detector. Distribution obtained from the CORSIKA-based light simulation (Geant4 tracking). The bump at ~ 1400 MeV corresponds to nearly vertical muons that deposit energy along ~ 7 m of LAr, assuming 2 MeV/cm of energy deposition (MIP).

Trigger	PMTs	S1 charge (PE) /muon	Obs. light yield (PE/MeV)	
			Average	Maximum
Random	All	1830	2.3	21.4
	6 TPB	650	0.8	10.2
	30 PEN	1180	1.5	13.1
CRT	All	1320	0.7	2.1
	6 TPB	590	0.3	1.1
	30 PEN	730	0.4	1.0

TABLE 8.15: Total S1 charge per cosmic muon (sum of all detecting PMTs) and observed light yield (average value from events and maximum value reached in an event) for two trigger modes.

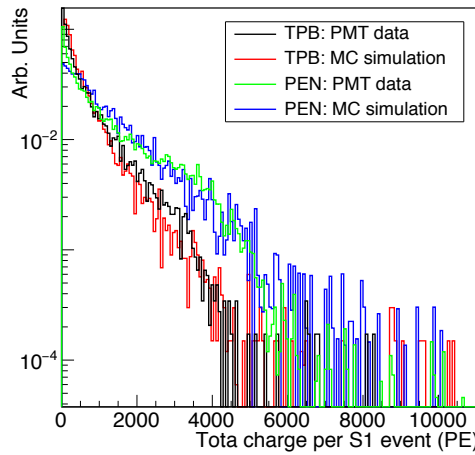


FIGURE 8.25: Normalized distributions of the total S1 charge per cosmic muon event (sum of all detecting PMTs) in random-trigger mode. Both data and MC (TPB and PEN) cases are displayed. It can be observed that the ADC saturation in data that limits the charge range is fairly reproduced in the MC.

is validated by the fair agreement between the average total S1 charge collected by the PDS per muon in data (1830 PE) and MC (1990 PE), see Figure 8.25. In a similar way, the observed light yield is computed for S1 signals acquired with CRT-trigger for comparison. The results are also contained in Table 8.15. In this case, based on the average track length in LAr observed in CRT-trigger data (9.4 m), an average deposited energy per muon 1880 MeV is obtained.

According to the values in Table 8.15, the complete PDS of ProtoDUNE-DP (36 PMTs) detects about 2.3 PE/MeV and 0.7 PE/MeV for random-trigger and CRT-trigger muon tracks, respectively. The latter case corresponds to an average track-PMT distance of 475 cm whereas the former comprises muons crossing the detector at any distance from the PMTs (from close to distant tracks, up to 7 m away from the PMTs). Since the scintillation photons from cosmic muons triggered with the CRTs are produced further from PMTs, the light is expected to undergo more attenuation. It is worth commenting that the difference between the average and maximum observed light yields is wider for random trigger

(almost 10 times) than for CRT-trigger events (3 times) due to the larger variety of events (energies and track topologies) in the first case.

The light yield is also shown in Table 8.15 separately for the two WLS groups in order to highlight the fact that the 6 TPB PMTs alone collect 1/3 of the total light. It can be retrieved that if the 36 PMTs had TPB coating (PEN foil), a total photon detection of about 5 PE/MeV (2 PE/MeV) would be reached in random trigger, on average. Therefore, in this particular PDS configuration, the use of PEN as the only WLS option would compromise the capability of the system as a calorimeter for low-energy particles. Considering TPB as the baseline WLS would make more feasible to accomplish the low-energy physics goals of the DUNE Far Detector like triggering on a supernova neutrino burst.

In conclusion, the better detection efficiency of the TPB-coated PMTs together with their stable performance during the detector operation confirm that TPB is an advisable WLS choice for future LArTPCs. However, PEN is an alternative that can also be considered if the easy installation prevails over the detection efficiency.

Light-based supernova neutrino burst trigger with a 12.1-kt LAr TPC

” Somewhere, something incredible
is waiting to be known.

— Carl Sagan

9.1 Introduction

One of the priorities within the science program of DUNE is the detection of galactic core-collapse supernova (SN) neutrinos [34, 110]. The basic features of a supernova neutrino burst were discussed in Section 1.6. It is expected that one of these extraordinary events occurs every 30 years [45] and, hence, one should occur during the experiment operation. As explained in Section 3.4.2, the sensitivity of DUNE to the ν_e flavor component of the supernova burst (SNB) will be unique among past, current and future neutrino experiments. It is important to notice that the energies of supernova neutrinos, in the few- to few-tens-of-MeV range, are very low compared to the GeV-neutrinos of the beam, and, hence, SN neutrino interactions involve particular triggering and reconstruction challenges. An enormous effort has been made so far to determine and optimize the detector capabilities on these tasks. An overview of selected studies on the SNB detection with DUNE can be found in [46].

Concerning the SNB trigger, several hundred neutrino interactions in a burst (from a SNB at 10 kpc) are expected to reach every DUNE far detector (FD) module over ~ 10 s. They will deposit $\mathcal{O}(20)$ MeV energy through ν_e charged-current (CC) interactions with argon nuclei (see Section 3.4.2). The better the DUNE sensitivity to low-energy events, the higher the SN neutrino detection probability. The main observables in the TPC will be short tracks (up to a few tens of cm) throughout the active volume along with low-energy scintillation light signals. Therefore, in DUNE, the trigger on a SNB can be done using either the TPC or the PDS, albeit the development of a redundant and efficient SNB triggering scheme based on both informations is envisioned given the rarity of a SNB in our galactic neighborhood and also the importance of the prompt alert that SN neutrinos can provide (DUNE is part of the SNEWS collaboration [47]). The trigger system exploits the time coincidence of multiple signals, either charge or light, over a timescale matching the

SN luminosity time evolution. Note that the SNB trigger strategy is defined together with the data acquisition (DAQ) system requirements since, in the case a SNB trigger is issued, the full detector information for a time range spanning several tens of seconds surrounding the trigger timestamp would be written to disk (about 115 TB of uncompressed data per FD module [193]). Thus, the SNB trigger is also a challenge from the point of view of the DAQ and the number of fake triggers must be minimized (kept below one per month) thanks to a highly efficient trigger algorithm.

The results presented in this chapter focus on the SNB trigger efficiency with the PDS of a 12.1-kt LAr TPC as the proposed DP DUNE FD (see Section 3.2.3.2). The DUNE studies reviewed in the next sections were carried out for the Technical Design Report (TDR) [179] of the experiment, namely, for the volume on the *DUNE Far Detector Dual-phase Technology* (to be publicly published soon). Besides, they are included in a DUNE publication about the expected DUNE capabilities for SNB detection [46].

First of all, detailed MC samples have been generated following the LArSoft light simulation chain already described in Section 7.4. Separate SN neutrino and background samples have been produced and their features are commented in Section 9.2. Then, the method to group the light signals found in the PMT waveforms (clustering approach) is described in Section 9.3 and the SN neutrino detection efficiency and background rate expected in the detector are calculated. These two last parameters are used as inputs to compute the SNB triggering efficiency in Section 9.4, where three WLS reflective foil scenarios providing different light-collection homogeneities are compared. Finally, Section 9.5 includes a brief discussion of the results and some key aspects of a LAr TPC for low-energy event detection, focusing on the light collection.

9.2 MC samples: supernova neutrinos and radiological backgrounds

Dedicated MC samples have been created to develop the SN trigger studies presented in this chapter. Details on the separate simulations of SN neutrinos and radiological backgrounds are contained in Table 9.1. The $\text{SN}\nu_e\text{CC}$ events are generated uniformly in the TPC active volume with MARLEY [180, 181] (Figure 9.1 left,) while the backgrounds are simulated using a dedicated model for the DP DUNE module (Figure 9.1 right). This radiological

MC sample	Event generator	#Events	PMT readout window
SN neutrinos	MARLEY	100k	16 μs
Backgrounds	Custom radiological model	40k	1 ms

TABLE 9.1: Parameters of the MC samples generated to study the light-based SN trigger efficiency in DUNE-DP. Common feature in the PDS-response step: 10^7 PMT gain. The baseline configuration reported in Section 7.4 is applied for the rest of parameters in the LArsoft simulation.

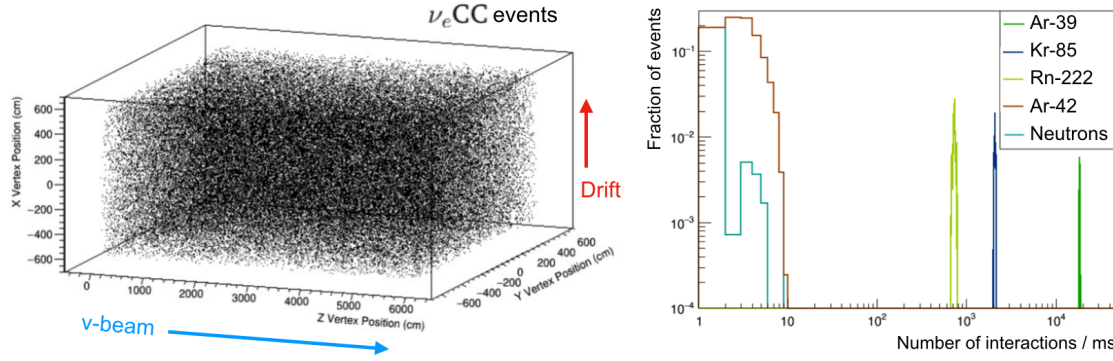


FIGURE 9.1: Left: 3D visualization of the interaction vertex position for the ν_e CC events simulated with MARLEY in the DUNE-DP active volume. The drift is along the x-axis and the PMTs are located at $x = -7$ m. Right: Distributions of the number of interactions per event (1 ms) for the different radiological sources included in the model for the background simulation in DUNE-DP.

model comprises ^{39}Ar , ^{42}Ar , ^{85}Kr , ^{222}Rn and impinging neutrons, being the activity of ^{39}Ar larger than the others by at least one order of magnitude. In Figure 9.1 right, the distributions of the number of interactions per ms are shown for the different background components. In the analysis, each background source is considered as a number of interactions (comparable to SN neutrino interactions) impacting on the SNB trigger evaluation. See Section 7.4 for further information on the LArSoft light simulation chain (including the event generators) and the baseline configuration applied.

9.3 Optical cluster reconstruction

In DUNE, a real-time algorithm should provide the trigger primitives by the continuous reconstruction of optical clusters, that is, by exploiting the space and time correlations among optical hits (scintillation light signals) detected by the PMTs. As it will be shown, the detection of several optical clusters in a certain time window is required to issue a SNB trigger according to the proposed off-line algorithm. This clustering approach is also employed in other non-beam physics studies in DUNE like nucleon decay (NDK) searches in order to accomplish both the event fiducialization of NDK candidates and the suppression of backgrounds induced by cosmic rays [179].

In this section, the clustering method developed and tested with the simulated PMT waveforms is presented. Besides, based on the clustering, the signal and background detection rates are estimated for three WLS reflective foil scenarios towards the calculation of the corresponding triggering efficiencies in the next section.

Using a custom hit-finding algorithm, optical hits are identified as pulses on single PMT waveforms with an amplitude larger than 10 ADC at a gain of 10^7 . This threshold corresponds to around 1/3 of the SPE amplitude (15 mV at a resolution of 0.5 mV/ADC) and >10 times the baseline fluctuation (0.8 ADC counts). Each optical hit is characterized by its channel, peak time, amplitude and integrated charge. Then, an optical cluster is

defined as a collection of optical hits presenting space and time correlations that indicate they were induced by the same underlying event of scintillation light in LAr. The cluster parameters under study are:

- **Maximum cluster duration:** time among all the PMT hits in a cluster (test values: 63 ns, 125 ns, 250 ns, 500 ns, 16 μ s, 8 μ s, 4 μ s, 2 μ s, 1 μ s).
- **Maximum time difference** between successive PMT hits in a cluster (test values: 50 ns, 100 ns, 200 ns, 400 ns and 800 ns).
- **Maximum spatial distance** between neighboring PMTs detecting the hits (test values: 1.5 m, 2.5 m, 3.5 m, 4.5 m and 5.5 m).
- **Minimum hit multiplicity:** minimum number of hits required per reconstructed optical cluster.

The last parameter (hit multiplicity) is set to the value that provides, for every combination of the other three parameters, a fixed and tolerable background rate: the higher the hit multiplicity, the lower the background cluster rate. The background rate (BGR) and SN neutrino detection efficiency (DE) are defined as follows:

$$\text{BGR} := \frac{\# \text{reconstructed background clusters}}{\text{total background sample time}} \quad (9.1)$$

$$\text{DE} := \frac{\# \text{reconstructed SN clusters}}{\# \text{SN events}} \quad (9.2)$$

where the total background sample time is 40 s and the number of SN events is 10^5 (Table 9.1).

For several test values of BGR (0.05 Hz, 0.10 Hz, 0.30 Hz and 1.00 Hz), a dedicated scan on the other free parameters is performed to find the cluster definition that maximizes the SN neutrino DE. Examples of these scans are displayed in Figure 9.2 for a BGR of 0.05 Hz¹, the lowest background cluster rate under study and baseline value in the following.

As explained in Section 7.4.2.1, three configurations of WLS reflective foils covering the inner walls of the field cage were initially considered for the proposed DP DUNE FD in order to enhance the light detection: 1) no foils, 2) half foils, only on the top half of the field cage, and 3) full foils, covering all the field cage inner walls. These options will be evaluated here from the point of view of the SN neutrino trigger.

The optimal clustering parameters for each foil scenario and for a BGR of 0.05 Hz are contained in Table 9.2, with the resulting SN neutrino DE. The optimal cluster definitions for the half-foil and full-foil cases are very similar: only the hit multiplicity threshold changes. However, with the no-foil geometry, more-populated clusters, as well as hits that are more spread in time, must be searched to maintain the fixed BGR level and achieve

¹The value of 0.05 Hz is considered a reasonable BGR and is chosen in these studies as it allows a SN neutrino DE around 10% with only half coverage with foils, which is sufficient to trigger on a SNB at the distance of interest (see Section 9.4).

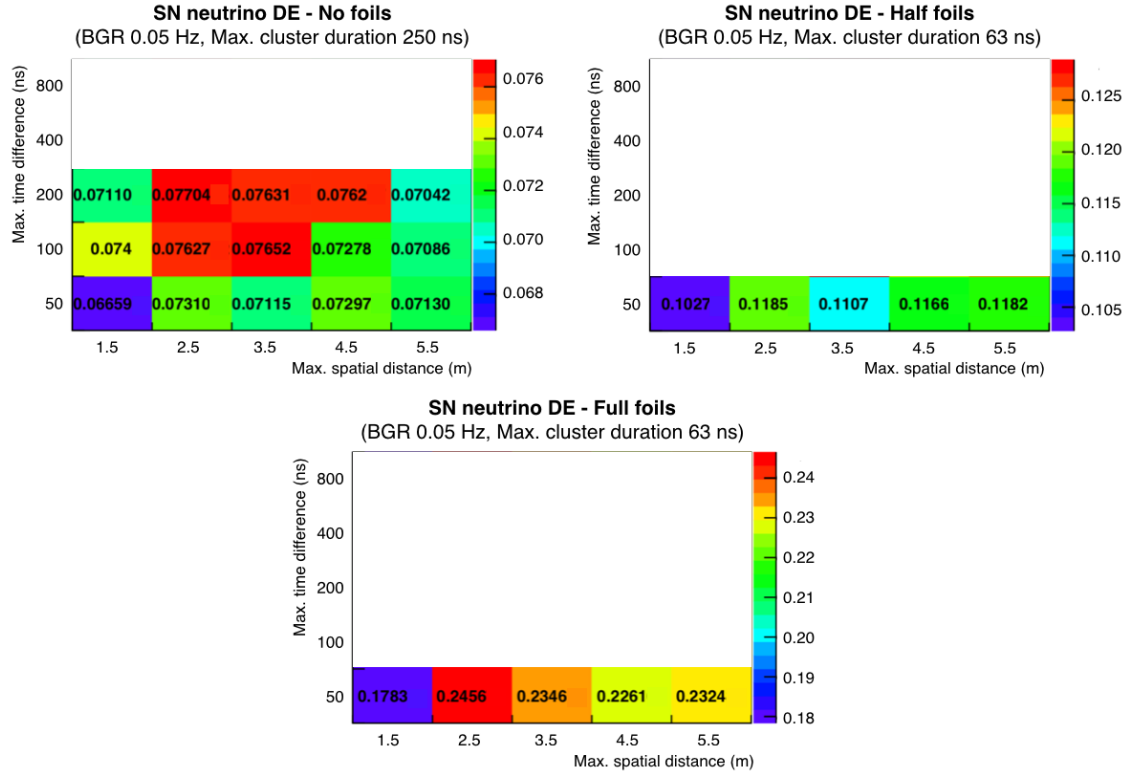


FIGURE 9.2: Scans on the clustering parameters for a BGR of 0.05 Hz to maximize the SN neutrino DE. The three foil configurations are displayed: no foils (top-left panel), half foils (top-right panel) and full foils (bottom panel). The color scale represents the SN neutrino DE reached with each combination.

Config.	Max. duration (ns)	Max. distance* (m)	Max. time* (ns)	Min. #hits	SN ν DE (%)
No-foil	250	2.5	200	77	7.7
Half-foil	63	2.5	50	46	11.8
Full-foil	63	2.5	50	51	24.5

TABLE 9.2: Optimal clustering parameters found for the different foil geometries in DUNE-DP and corresponding ν_e CC-signal DE, for a BGR of 0.05 Hz. *Between hits in the cluster.

the highest SN neutrino DE. The SN neutrino DE is mainly determined by the required hit multiplicity, which is, in turn, dependent on the fixed BGR level. However, the amount of detected optical hits is also different for each foil configuration since the larger the foil coverage, the higher the light detection. As a result, the SN neutrino DE with full foils is higher than with half foils despite the hit multiplicity threshold is slightly higher in the first case. The advantages of the different foil options will be discussed later in terms of the final SNB trigger efficiency which will be evaluated in the next section.

9.4 Supernova burst triggering efficiency

As stated before, DUNE will count on a redundant and highly efficient SNB triggering scheme in order to guarantee the detection of the SN neutrinos reaching the FD modules. The trigger on such low-energy signals can be done using either TPC or PDS informations, but the combination of both systems provides a more robust trigger system. In this section, the efficiency of the light-based SNB trigger is investigated for the DUNE-DP design. The fixed BGR of 0.05 Hz and the SN neutrino DE for each foil configuration (from the optimal clustering reported in the previous section) are employed to compute the SNB triggering efficiency (TE) as a function of the SN distance following three steps (further described in the next sections):

1. Calculate the minimum cluster multiplicity during a certain time window to issue a trigger with tolerable fake trigger rate.
2. Compute the SNB TE as a probability function that depends on the cluster multiplicity threshold and other parameters; the result is obtained as a function of the number of SN events.
3. Convert TE vs. number of SNB events into TE vs. SN distance using a theoretical assumption that connects both SN quantities.

9.4.1 Step 1: minimum cluster multiplicity

During the years that DUNE will be operated, the DAQ system will record data for the ~ 100 s surrounding every SNB trigger timestamp. Thus, the streaming data generated by the SNB trigger that the DAQ will have to handle will be huge. Namely, 115 TB of uncompressed data per FD module are expected from each trigger instance, which means 1.4 PB/year [193]. As a consequence, the DAQ constrains the maximum rate of fake SNB triggers to one per month. The minimum cluster multiplicity (MCM) to issue a trigger is set by this DAQ requirement and by the BGR level. A third parameter involved at this point is the analyzed burst time window (BTW) or time of interest in the online cluster reconstruction (note that a different time interval can be analyzed in the later off-line analysis).

The fake trigger rate (FTR) is estimated with a Poisson distribution as:

$$FTR(N) := BGR \times \left(\sum_{\lambda=N}^{\infty} \frac{e^{-\mu} \mu^{\lambda}}{\lambda!} \right) \quad (9.3)$$

$$\mu := BGR \times BTW \quad (9.4)$$

where N is the minimum number of reconstructed background clusters. The Poisson function above is replaced by a Gaussian for $\mu > 10$. In Figure 9.3, the fake trigger rate is displayed as function of N for several test inputs to verify the impact of the different

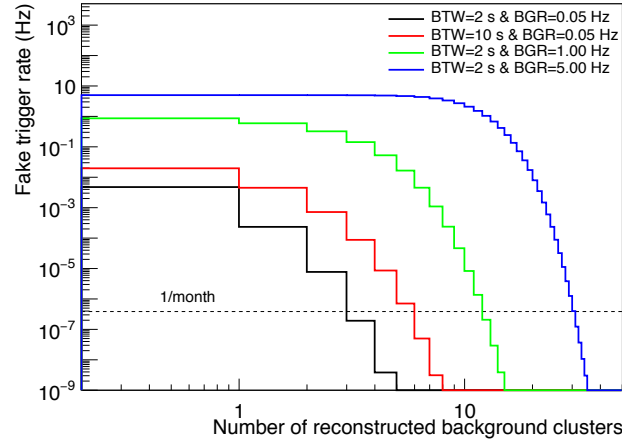


FIGURE 9.3: Fake trigger rate vs. number of reconstructed background clusters for several test burst time windows (BTW) and background cluster rates (BGR).

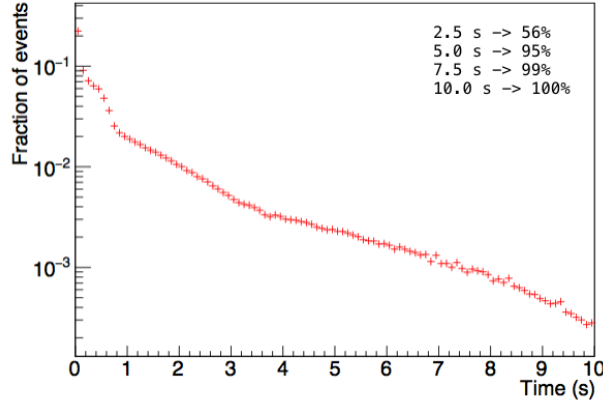


FIGURE 9.4: First 10 s of the (normalized) SNB time profile. The relative fractions of events within certain time intervals are indicated. Note that the SN neutrino signal is not completely contained in the first 10 s.

parameters. Note that the higher the BGR, the higher the MCM needed to meet the DAQ requirement (black vs. green or blue curves). Likewise, the longer the BTW, the higher the required MCM (black vs. red curve).

The SNB time profile that is assumed in these studies can be seen in Figure 9.4. It can be observed that more than half of the events are expected within the first 2.5 s of burst. The optimal BTW to analyze must be determined in view of the final TE since this variable is also involved in the next steps. After a set of scans on the BTW value (one scan per foil geometry), it is found that a window length of 2 s provides the best TE results for any foil case. In this way, for a BGR of 0.05 Hz and a BTW of 2 s, a MCM of 3 is required for a fake trigger rate of $<1/\text{month}$ (DUNE requirement).

At this point, the SN neutrino DE values previously computed (Table 9.2) can be evaluated dividing the MCM of 3 by the DE. For the no-foil (DE=7.7%), half-foil (11.8%) and full-foil (24.5%) scenarios, at least ~ 39 , ~ 25 and ~ 12 $\text{SN}\nu_e\text{CC}$ interactions must occur

in the DP module within 2 s, respectively, to obtain a non-negligible trigger efficiency. As it will be explained in Section 9.4.3, several hundreds (tens) of SNB neutrino interactions per DP module are expected for a SN at 10 kpc (20 kpc) and, thus, the SN neutrino DE values assumed in these studies ($\sim 8\text{-}25\%$) should be sufficient to accomplish the SNB trigger goal. Nevertheless, the efficiency level of the trigger system is critical and, hence, it will be investigated in the next sections.

9.4.2 Step 2: SNB trigger efficiency vs. number of SN events

The second step consists in calculating the SNB TE as a function of the number of SN events in the detector. Again, a Poisson distribution is employed to define the efficiency:

$$\text{SNB TE}(N_{SN}) := \sum_{\lambda=MCM}^{\infty} \frac{e^{-\mu} \mu^{\lambda}}{\lambda!} \quad (9.5)$$

$$\mu := \text{signal} + (BGR \times BTW) \quad (9.6)$$

being the signal:

$$\text{signal} := N_{SN} \times DE \times \int_0^{BTW} f(t) dt \quad (9.7)$$

where N_{SN} is the number of SN events in the detector and $f(t)$ is the burst time profile of Figure 9.4.

Figure 9.5 shows the SNB TE curves for the different foil geometries, and assuming a BGR of 0.05 Hz and the SN neutrino DE values from the optimal clustering. The optimal BTW of 2 s that was determined in the previous section (MCM of 3) is also employed in the equations above for the TE calculation. In view of the obtained SNB TE curves,

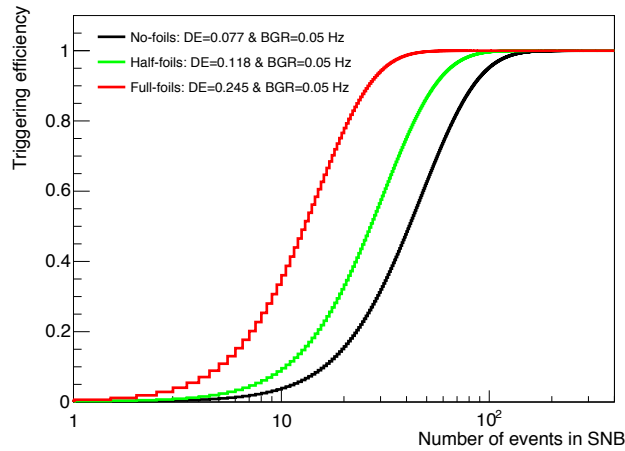


FIGURE 9.5: SNB TE as a function of the number of SN events in the DP module. The no-foil (black), half-foil (green) and full-foil (red) cases are compared. The MCM of 3 obtained in the previous section for a maximum fake trigger rate of one per month is used.

the differences among the foil cases become significant if less than ~ 100 SN events are detected and, hence, the SNB TE is also investigated in terms of the SN distance in the next step.

9.4.3 Step 3: SNB trigger efficiency vs. SN distance

The SNB triggering efficiency as a function of the SN distance is obtained by converting the number of events in the horizontal axis of Figure 9.5 into distance to the SN using the theoretical assumptions shown in Figure 9.6, where some distances of interest are indicated with vertical black lines. The distributions contain significant uncertainties introduced by the SNB models [46]. Here, the standard one represented with a solid line is chosen.

The SNB TE results in terms of SN distance are reported in Figure 9.7 and Table 9.3. It can be concluded that the PDS of DUNE-DP should provide full SNB trigger efficiency for a core collapse at 10 kpc as well as a trigger efficiency in excess of 90% for any foil configuration at 20 kpc (Galaxy edge). However, the SNB TE reached at 50 kpc would not be sufficient to trigger on a SN at the Large Magellanic Cloud, not even with full foil coverage.

Regarding the foil implementation, the impact of the WLS reflective foils becomes more important at large SN distances. Both the half-foil and full-foil configurations expand the distance range where an efficient SNB trigger ($>90\%$) can be achieved but, according to the results presented here, reflective foils are not as critical as for other physics goals such as the NDK searches [179]. As described in Section 3.2.3.2, the half-foil geometry is the baseline one in DUNE-DP because it increases the detected light yield in the upper part of the TPC and mitigates the non-uniformity of the light collection, factors that play a crucial

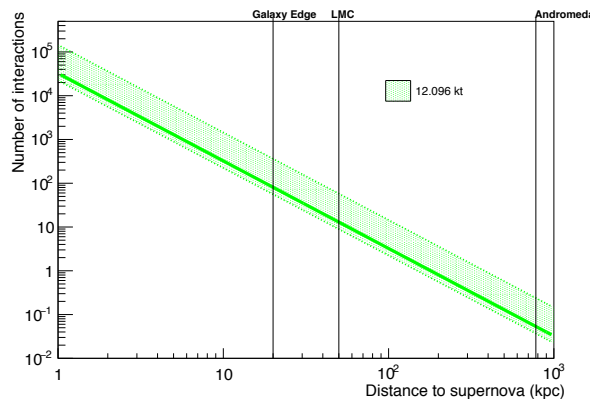


FIGURE 9.6: Time-integrated expected number of $\text{SN}\nu_e\text{CC}$ interactions (>10 MeV neutrino energy) in 12.1 kt of LAr (active mass of one DP FD module) as a function of the SN distance. The different green lines correspond to different SNB models [46]. The vertical black lines indicate the approximate distances at which the Milky Way edge (20 kpc), the Large Magellanic Cloud (LMC, 50 kpc) and the Andromeda galaxy (778 kpc) are from Earth.

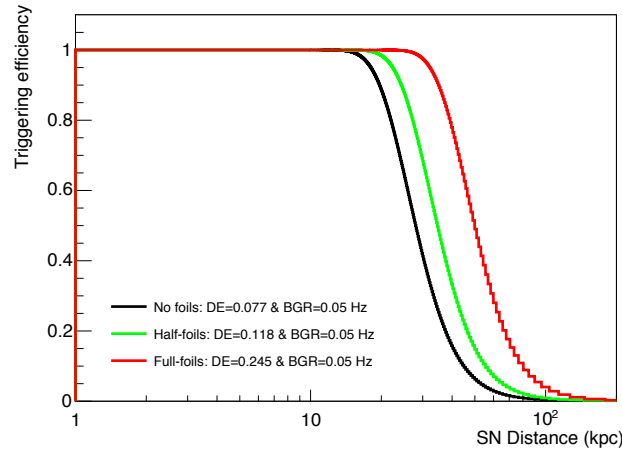


FIGURE 9.7: SNB triggering efficiency as a function of the SN distance. The no-foil (black), half-foil (green) and full-foil (red) cases are displayed for comparison.

Config.	SN ν DE (%)	SNB triggering efficiency (TE) (%)			Limit* for TE>90% (kpc)
		10-kpc SNB	20-kpc SNB	50-kpc SNB	
No-foil	7.7	100	93.7	8.0	20.3
Half-foil	11.8	100	98.6	32.2	25.1
Full-foil	24.5	100	99.9	57.6	36.3

TABLE 9.3: Results of the SNB triggering studies. The different foil configurations are compared. All the cases correspond to 0.05-Hz BGR and 2-s BTW (3 MCM). *Maximum SN distance.

role in NDK searches. In addition, at least half foils are advisable to enhance the efficiency of the SNB trigger system.

9.5 Discussion

Core-collapse SN are expected to occur a few times per century (every ~ 30 years [45]) at a most-likely distance of ~ 10 -15 kpc from Earth. According to the simulation studies reported in this chapter (included in [46, 129, 179]) the projected DUNE-DP PDS alone should be able to trigger with $>90\%$ efficiency on a SNB at a distance up to ~ 25 kpc, so it would cover the entire Milky Way. Besides, the PDS performance would meet the DAQ requirement of a maximum fake trigger rate of one per month. The studies also demonstrate that the baseline configuration of WLS reflector foils (half-foil geometry) is desirable to improve the SNB trigger capability. The alternative choices would fulfill the 90%-requirement up to the Galaxy edge (20 kpc), albeit roughly in the no-foil case.

The main conclusion from the studies in this chapter is the importance of counting on a PDS to efficiently detect the scintillation light produced in all the volume of a LAr TPC. In fact, the enhancement of the light collection in a LAr detector (using, for example, reflective

surfaces like the foils studied here, xenon-doped LAr [90] or an extensive coverage with light sensors like X-ARAPUCAs [117]) is crucial to achieve the detector sensitivity needed to study low-energy events such as SN neutrino interactions.

An approach to upgrade DUNE capabilities for low-energy physics is the DUNE low-background module design [194, 195] consisting of a bulk of low radioactivity underground argon without internal components for a better radiopurity. It would include water and plastic shielding for neutrons as well as the addition of reflectors and a large coverage with SiPMs. This low-background FD concept, still under development, would be beneficial not only for supernova and solar neutrino physics studies but also for WIMP dark matter detection.

To sum up, the promising results from the simulation studies presented in this chapter point out the excellent performance of the highly efficient PMTs, fundamental in the challenging low-energy regime of SN neutrino interactions. Thus, the robust DUNE-DP PDS configuration should be taken into account in the design of future LAr detectors, especially if they intend to perform low-energy physics studies or trigger on non-beam events.

Conclusions

As part of the DUNE far detector (FD) R&D program at CERN, the 6-m drift ProtoDUNE Dual Phase (DP) detector collected data in 2019-2020 with cosmic rays. It was a crucial step towards the operation of a DP liquid-argon (LAr) time-projection-chamber (TPC) at the kt-scale. Despite the challenges and issues faced during the ProtoDUNE-DP performance that prevented from reaching the nominal conditions, valuable experience and many results of interest for the LAr TPC community were obtained. ProtoDUNE-DP had a photon detection system (PDS) formed of 36 photomultiplier tubes (PMTs) as well as a light calibration system (LCS) to monitor the PMT response.

Before the PDS installation in the detector, its components were carefully characterized both at room (RT) and cryogenic (CT) temperatures at CIEMAT laboratory. The characterization of 40 Hamamatsu R5912-20Mod cryogenic PMTs was carried out to verify the good performance at CT of each device in terms of noise (dark current) and signal amplification (gain). On average, a gain drop of $71 \pm 14\%$ was measured at CT with respect to RT at 10^7 gain for the 40 PMTs. These measurements were essential to identify and replace two defective PMTs. As a result, all the PMTs were operational since the beginning of the running of ProtoDUNE-DP and they exhibited an excellent performance during all the data-taking period.

In a similar way, the LCS components were characterized both at RT and CT prior to the installation. The LCS was designed to minimize the light attenuation, found to be $<19. \pm 0.4$ dB from the flange to the PMTs, illuminating all PMTs at the single photoelectron (SPE) level homogeneously. The full calibration chain was validated at CIEMAT laboratory and, once in the detector, the LCS performed stably and allowed the regular gain calibration of the PMTs.

Further research at the laboratory on the PMT behaviour in cryogenic conditions was reported in this dissertation. On the one hand, the analysis of the PMT response linearity with the light intensity and pulse frequency provided a better understanding of the expected PMT behaviour in the detector. On the other hand, PMT tests with over-pressure demonstrated, for the first time, that the device can operate at CT up to at least 4-bar absolute pressure without any mechanical change and with only the expected performance variations due to the temperature change.

In ProtoDUNE-DP, the detection by all the PMTs of scintillation photons produced up to 7 m away from them (achieved for the first time in a LAr detector) and the good light signal-to-noise ratio (>11 at 10^7 gain) validated the PDS design for future long-drift detectors. Concerning an alternative LCS based on two fibers installed in the upper part of ProtoDUNE-DP, it was tested for the first time and results compatible with the baseline

LCS configuration were obtained (-9% of average discrepancy), albeit further optimization of the design is needed.

The study of several aspects relevant for the light collection in a LAr TPC was developed in this work based on the ProtoDUNE-DP light data. First of all, the background SPE pulses detected by the PMTs were characterized in amplitude, width and frequency (~ 170 - 350 kHz in absence of fields). The expected low-energy pulse rate with no fields is ~ 60 kHz according to an estimation that takes into account natural radioactivity, PMT dark current and muon signals, and, hence, it does not match the measured SPE rate. Therefore, further investigation to understand the origin of the extra SPE rate component in ProtoDUNE-DP, also observed in other LAr detectors, is still required.

The cosmic-muon data taken with the PDS of ProtoDUNE-DP enabled to perform relevant measurements and explore several physics parameters of interest thanks to the high purity of the LAr medium and the large size of the detector. Some of the aspects discussed in the thesis were:

- The reduction of the light yield due to the drift field: a modest electric field (~ 0.09 kV/cm) was able to reduce the recombination contribution to the light yield by 17%, result consistent with the Birks' law.
- The Rayleigh scattering affecting the light propagation: a Rayleigh scattering length of 99.9 cm (last measurement reported in [77]) reproduced better the data than a length of 61 cm (test value motivated by the results presented in [101], [102] and [96]).
- The VUV reflectance of the detector materials: the reflected light can contribute to the total collected light by 8-11% and, hence, dedicated measurements of the specific reflectivities become critical.
- The relative PEN-TPB response: a PEN-TPB charge ratio of 0.178 ± 0.001 was measured for a data sample corresponding to an average collected charge of ~ 200 PE and ~ 35 PE by TPB and PEN PMTs, respectively. In addition, it was found that the 6 TPB PMTs alone collected $> 1/3$ of the total light detected by the complete system and that the observation of photons produced > 5 m away from the PMTs would be compromised if the PDS were only based on PEN PMTs.
- The flux of cosmic muons crossing ProtoDUNE-DP: a muon flux of 148^{+8}_{-11} Hz/m² was obtained, in agreement with other measurements given in the literature. Besides, the S1 rate variation was found to be small throughout seven months (~ 2 -5%) and also within the same data sample ($< 1\%$), which confirmed the stable performance of the system.

The last part of the thesis was dedicated to the analysis of the supernova burst trigger efficiency with the PDS of a 12.1-kt active mass LAr TPC as the one proposed for a DP DUNE FD. Three different wavelength shifters (WLS) reflective foil scenarios (full, half and null coverage of the field cage inner walls) were compared. The supernova triggering efficiency was computed as a function of the supernova distance and it was concluded that

the PDS of DUNE-DP should provide a trigger efficiency in excess of 90% at 20 kpc (Galaxy edge) for any foil configuration and that at least half-foil coverage would be desirable to improve the trigger capability.

The main results reported in this document have led to different publications. They can be found in [118, 151, 152] (PDS and LCS validations before the installation), [90] (ProtoDUNE-DP results on the light detection, in preparation) and [46, 129, 179] (light-based SNB triggering studies in DUNE-DP). It has to be noted that the research work of this thesis developed on the PDS and LCS of ProtoDUNE-DP has included the participation in different activities besides the data analysis, such as the characterization, installation, commissioning and operation of the systems, and the data taking.

Significant results from the ProtoDUNE-DP light data analysis and DUNE-DP light simulation studies have been presented over this dissertation. While some of the findings were related to the scintillation light properties in LAr, others concerned the performance of PMTs in cryogenic conditions. It is worth remarking that these pioneering results (from the longest-drift LAr TPCs ever operated or envisioned) are independent of the TPC technology and they are considered also useful for LAr detectors beyond neutrino experiments. For instance, LAr-based experiments requiring low background, in which the scintillation light information is exploited as well, can profit from these key investigations. Some transverse aspects under study were the PMT basic response and linearity at CT, the PMT calibration, the evaluation of the impact of different parameters affecting the scintillation light production and propagation in LAr, the TPB and PEN efficiencies as WLS for PMTs and the light collection enhancement using WLS reflective panels. In summary, this work is an important contribution towards both a better understanding of the scintillation light mechanisms in LAr and the PDS design optimization for future LAr-based experiments.

Conclusiones

Como parte del programa de I+D en el CERN para el detector lejano de DUNE, el detector de 6 m de distancia de deriva ProtoDUNE Dual Phase (DP) adquirió datos con rayos cósmicos en 2019-2020. Ha sido un paso clave hacia la operación de una cámara de proyección temporal de argón líquido (*liquid-argon time-projection-chamber*, LAr TPC) a gran escala. A pesar de los retos y problemas afrontados durante la operación de ProtoDUNE-DP, que impidieron alcanzar las condiciones nominales, se ha obtenido una valiosa experiencia, además de muchos resultados de interés para la comunidad de LAr TPCs. ProtoDUNE-DP tuvo un sistema de detección de luz (*photon detection system*, PDS), formado por 36 fotomultiplicadores (*photomultipliers*, PMTs), y un sistema de calibración del PDS (*light calibration system*, LCS) para monitorizar la respuesta de los PMTs.

Antes de la instalación del PDS en el detector, se caracterizaron cuidadosamente sus componentes a temperaturas tanto ambiente (TA) como criogénica (TC) en el laboratorio del CIEMAT. La caracterización de 40 PMTs criogénicos R5912-20Mod de Hamamatsu se llevó a cabo para verificar el buen funcionamiento a TC de cada sensor en términos de ruido (corriente oscura) y amplificación de la señal (ganancia). En media, se ha observado una caída de ganancia de $71 \pm 14\%$ a TC con respecto a TA a ganancia de 10^7 para los 40 PMTs. Estas medidas fueron esenciales para identificar y reemplazar dos PMTs defectuosos. Como resultado, todos los PMTs funcionaron desde el comienzo de la operación de ProtoDUNE-DP y exhibieron una excelente respuesta durante todo el periodo de toma de datos.

De manera similar, los componentes del LCS se caracterizaron a TA y TC antes de la instalación. El LCS se diseñó para minimizar la atenuación de la luz, de $<19. \pm 0.4$ dB desde el *flange* hasta los PMTs según las medidas, iluminando todos los PMTs al nivel de un solo foto-electrón (*single photo-electron*, SPE) homogéneamente. La cadena completa de calibración se validó en el laboratorio del CIEMAT y, una vez en el detector, el LCS funcionó de manera estable y permitió la calibración regular de los PMTs.

En esta tesis, se presenta una investigación adicional del comportamiento del PMT llevada a cabo en el laboratorio en condiciones de criogenia. Por un lado, el análisis de la linealidad de la respuesta del PMT con la intensidad de la luz y la frecuencia de los pulsos ha proporcionado una mejor comprensión del comportamiento del PMT esperado en el detector. Por otro lado, pruebas del PMT con sobrepresión han demostrado, por primera vez, que el sensor puede operar a TC hasta al menos 4 bar de presión absoluta sin ningún cambio mecánico y con solo las variaciones de funcionamiento esperadas por el cambio de temperatura.

En ProtoDUNE-DP, la detección por todos los PMTs de los fotones de centelleo producidos a distancias de hasta 7 m de ellos (conseguida por primera vez en un detector de argón líquido) y el buen cociente de señal-ruido (> 11 a ganancia de 10^7) han validado el diseño del PDS para futuros detectores con larga distancia de deriva. Respecto al LCS alternativo, basado en dos fibras instaladas en la parte superior de ProtoDUNE-DP, fue probado por primera vez y se obtuvieron resultados compatibles con la configuración de LCS original (-9% de discrepancia media), aunque se necesita más optimización del diseño.

En este trabajo, se ha desarrollado, usando datos de luz de ProtoDUNE-DP, el estudio de varios aspectos relevantes para la detección de luz en una LAr TPC. En primer lugar, se caracterizó el fondo de pulsos a nivel SPE detectado por los PMTs en amplitud, anchura y frecuencia (~ 170 -350 kHz en ausencia de campo eléctrico). El ritmo esperado de pulsos de baja energía sin campo es ~ 60 kHz, según una estimación que tiene en cuenta la radiactividad natural, la corriente oscura del PMT y las señales de muones y, por tanto, no cuadra con el ritmo de pulsos SPE medido. Así, se requiere más investigación para entender el origen de la contribución adicional del ritmo de SPE en ProtoDUNE-DP, también observada en otros detectores de argón líquido.

Los datos de muones cósmicos tomados con el PDS de ProtoDUNE-DP han permitido realizar medidas relevantes y explorar varios parámetros físicos de interés gracias a la alta pureza del argón líquido y al gran tamaño del detector. Algunos de los aspectos discutidos en esta tesis han sido:

- La reducción de la producción de luz debida al campo de deriva: un campo eléctrico modesto (~ 0.09 kV/cm) fue capaz de reducir la componente de luz originada por recombinación en un 17%, resultado consistente con la Ley de Birks.
- La dispersión Rayleigh, que afecta a la propagación de la luz: una longitud de dispersión Rayleigh de 99.9 cm (última medida presentada en [77]), reproduce mejor los datos que una longitud de 61 cm (valor de prueba motivado por los resultados de [101], [102] y [96]).
- La reflectividad de los materiales del detector para luz ultravioleta: la luz reflejada puede contribuir al total de la luz detectada en un 8-11% y, por tanto, disponer de medidas específicas de las reflectividades es crítico.
- La respuesta relativa PEN-TPB: se ha medido un cociente en carga PEN-TPB de 0.178 ± 0.001 para una muestra de datos correspondiente a una carga media de ~ 200 PE y ~ 35 PE detectada por PMTs con TPB y PEN, respectivamente. Además, se ha observado que los 6 PMTs con TPB solos detectan $> 1/3$ de la luz total recogida por el sistema completo y que la detección de fotones producidos a > 5 m de los PMTs estaría comprometida si el PDS solamente se basara en PMTs con PEN.
- El flujo de muones cósmicos que cruza ProtoDUNE-DP: se ha obtenido un flujo de muones de 148^{+8}_{-11} Hz/m², en acuerdo con otras medidas dadas en la literatura. Además, se ha comprobado que la variación del ritmo de señales S1 fue pequeña a

lo largo de siete meses ($\sim 2\text{-}5\%$) y también dentro de la misma muestra de datos ($<1\%$), lo cual confirma el funcionamiento estable del sistema.

La última parte de la tesis se ha dedicado al análisis de la eficiencia de disparo de estallidos de supernova con el PDS de una LAr TPC de 12.1 kt de masa activa como el propuesto para un detector lejano de doble fase en DUNE. Se han comparado tres escenarios diferentes de láminas reflectantes con desplazador de longitud de onda (recubrimiento completo, medio o nulo de las paredes internas de la jaula de campo). La eficiencia de disparo de sucesos de neutrinos provenientes de supernovas ha sido calculada en función de la distancia a la supernova, concluyendo que el PDS de DUNE-DP debería proporcionar una eficiencia de disparo por encima del 90% a 20 kpc (borde de la galaxia) para cualquiera de las configuraciones de láminas reflectantes y que al menos una cobertura media sería recomendable para mejorar la capacidad de disparo.

Los principales resultados presentados en este documento han conducido a diferentes publicaciones. Pueden encontrarse en [118, 151, 152] (validaciones del PDS y del LCS antes de la instalación), [90] (resultados de ProtoDUNE-DP en la detección de luz, en preparación) y [46, 129, 179] (estudios del disparo de supernova basado en la luz en DUNE-DP). Debe tenerse en cuenta que el trabajo de investigación de esta tesis desarrollado en el PDS y el LCS de ProtoDUNE-DP ha incluido la participación en distintas actividades además del análisis de datos, como la caracterización, instalación, puesta a punto y operación de los sistemas, así como la propia toma de datos.

A lo largo de esta tesis, se han discutido resultados significativos del análisis de la luz en ProtoDUNE-DP y de los estudios de simulación de la luz en DUNE-DP. Mientras que algunos de los hallazgos tienen relación con las propiedades de la luz de centelleo en argón líquido, otros tienen que ver con el funcionamiento de los PMTs en diferentes condiciones de operación y configuraciones. Merece la pena destacar que estos resultados pioneros (de las mayores LAr TPCs jamás operadas o concebidas) son independientes de la tecnología de TPC y son considerados también útiles para detectores de argón líquido más allá de los experimentos de neutrinos. Por ejemplo, los experimentos basados en argón líquido que requieren bajo fondo, en los cuales también se explota la luz de centelleo, pueden beneficiarse de estas investigaciones clave. Algunos aspectos transversales estudiados han sido la respuesta básica y linealidad del PMT a TC, la calibración de PMTs, la evaluación de distintos parámetros que afectan a la producción y propagación de la luz en argón líquido, las eficiencias del TPB y del PEN como desplazadores de longitud de onda y la mejora de la detección de la luz usando paneles reflectantes con desplazador de longitud de onda. En resumen, este trabajo supone una contribución importante tanto para un mejor entendimiento de los mecanismos de la luz de centelleo en argón líquido como para la optimización del diseño del PDS en futuros experimentos basados en argón líquido.

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