



Summer Student Programme 2023

R&D on LAr-TPC for neutrinos and rare events

Supervisors : Francesco PIETROPAOLO (CERN) & Pascal PRALAVORIO (CPPM)

Abstract

In physics, new particles or new phenomena might be discovered from rare event detections. Several ambitious programs have been launched world-wide in the search for rare events. New experiments have been developed from Liquid Argon Time Projection Chamber technology aimed at discovering new particles that explain the presence of dark matter in the universe (Darkside-20k), or to measure the parameters of CP violation in the neutrino sector that might explain the matter-antimatter asymmetry (DUNE). An intense R&D is carried out at CERN. For my internship at CERN, in Switzerland, I joined both groups, DarkSide-20k and ProtoDUNE.

Lucas BOISTAY

Summer 2023

Contents

Introduction	3
1 Calibration of DarkSide-20k experiment	3
1.1 Dark Matter	3
1.1.1 Particle physics	3
1.1.2 Proof of existence and properties of Dark Matter	4
1.1.3 Dark Matter candidates and WIMPs	5
1.2 DarkSide-20k experiment	6
1.2.1 Liquid Argon Dual Phase TPC	7
1.2.2 Challenges of DarkSide-20k calibration	7
1.3 Long run Mock-up calibration at LAr and LN2 temperatures	8
1.3.1 Reaching stability during LN2 tests	9
1.3.2 LN2 tests	10
1.3.3 LAr tests	12
1.4 Extrapolation to DS-20k	13
2 Proto-DUNE	14
2.1 Neutrinos and DUNE experiment	14
2.1.1 Neutrinos	14
2.1.2 Dune experiment	14
2.1.3 ProtoDune at CERN	15
2.1.4 50 L LAr-TPC setup	17
2.2 Cosmic muons analysis	18
2.2.1 Cosmic events	19
2.2.2 Event filtering	20
2.2.3 Charge deposition landau distribution	21
2.2.4 Normalisation	23
2.3 Conclusion	23

Introduction

During my post-bachelor's internship, I had the privilege of joining the CERN Summer Student Program. During 11 weeks, I contributed to two Time Projection Chamber experiments. Initially, my focus was on validating the calibration process for the upcoming DarkSide-20k detector, designed to detect Dark Matter. Afterwards, I collaborated on the DUNE experiment, dedicated to neutrino detection. My specific contributions involved analysing data from cosmic muon tracks within a 50 L LAr-TPC. This latter segment of my experience at CERN served as a supplementary phase, improving my understanding of the wider experimental landscape.

1 Calibration of DarkSide-20k experiment

1.1 Dark Matter

1.1.1 Particle physics

Elementary particle physics is described by the Standard Model (SM). It is composed of matter (six quarks, six leptons), forces (four gauge bosons) and finally the Higgs particle, which was discovered at the Large Hadron Collider (LHC) in July 2012 at CERN. This is a complete model that is able to reproduce the results of collisions between elementary particles from keV to TeV with great precision.

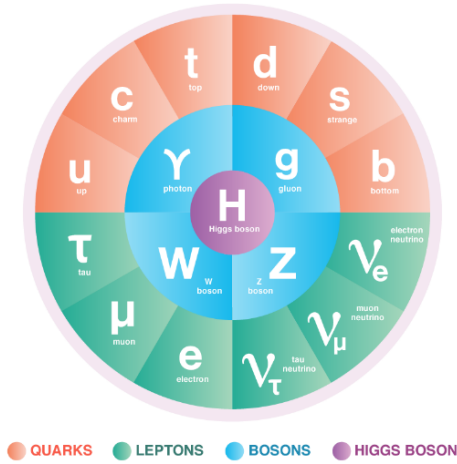


Figure 1: The Standard Model includes the matter particles (quarks and leptons), the force carrying particles (bosons), and the Higgs boson.

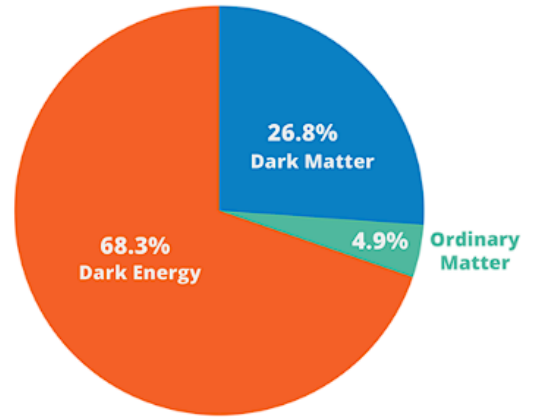


Figure 2: Pie chart of the estimated matter-energy content of the universe as of 2020. Ordinary matter gathers the elementary particles of Figure 1.

Since 50 years, particle physics is facing a phase transition. Motivated firstly to explain behaviour at infinitesimal scale (nuclear scale), the field is trying to explain the Universe as a whole, which requires postulating new particles (see Section 1.1.3). Searching for new particles was for a long time related to design more energetic accelerators. Unfortunately, it is becoming increasingly difficult to reach higher energies (= higher masses) at colliders. Moreover, there might be lighter particles that do not require colliders to be observed. This explains the new birth of astroparticle experiments for detecting these new particles.

1.1.2 Proof of existence and properties of Dark Matter

Several observations in astrophysics and cosmology require the existence of a new form of matter, called Dark Matter (DM). The two most convincing proofs are recalled here :

First, in galaxies, the star orbital speed must follow the 3rd Kepler's law :

$$v(r) \propto \sqrt{\frac{GM(r)}{r}} \quad (1)$$

where r is the distance between the star and the centre, $M(r)$ is the central mass the star is orbiting around and G the gravitational constant. Away from the centre of galaxies, $M(r)$ become constant and the velocity should decrease in $r^{-1/2}$. However, this is not what is observed. Figure 3 shows that in the M33 galaxy, star velocity is increasing with distance (continuous line) compared to the theory (short-dashed line). This suggests that there must be additional mass present in galaxies, $M(r) \propto r$, forming a halo of invisible matter, called Dark Matter, as it does not interact with the electromagnetic force (carried by photons).

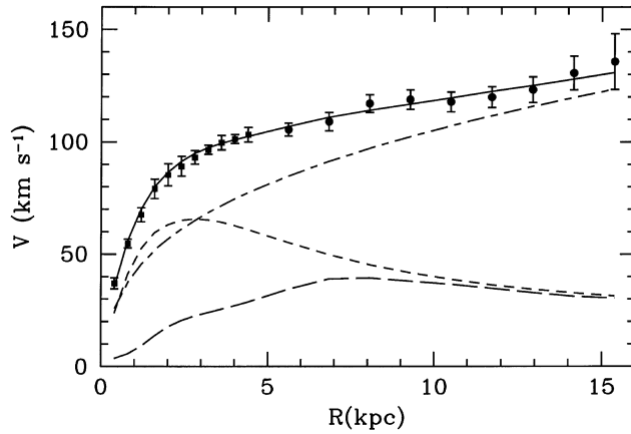


Figure 3: Rotation speed of stars in M33 galaxy (points) compared with the best-fitting model (continuous line) [1]. Also shown are the halo contribution (dot-dashed line), the stellar disc (short-dashed line) and the gas contribution (long-dashed line).

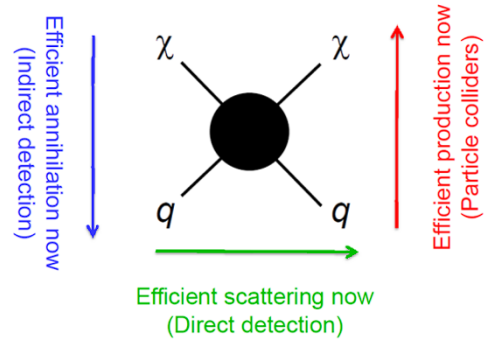


Figure 4: Interaction diagram between DM particle (χ) and SM quark (q).

The largest proof of the existence of DM can be found in the spectral analysis of temperature on anisotropies of the Cosmic Microwave Background (CMB) which can measure the ratio of baryonic matter (atoms) and DM in the universe. From WMAP and PLANCK data [2], and assuming the Λ Cold Dark Matter model, scientists found that the universe is composed by 25% of DM, and only 5% of baryonic matter (see Figure 2)¹.

From a general perspective, the DM have to follow these properties :

- **Coupled to gravitational field :** DM interact through gravity. It exerts gravitational force on ordinary matter and on other DM particles.

¹The rest of it, around 68%, is Dark Energy.

- **Not coupled to electromagnetic field** : DM does not interact with the electromagnetic field. It does not emit, absorb or reflect any radiation.
- **Weakly coupled to particles** : DM should have very weak interactions with the other Standard Model particles.
- **Stable matter** : Since DM is still present, it needs to be stable on cosmological scales.

1.1.3 Dark Matter candidates and WIMPs

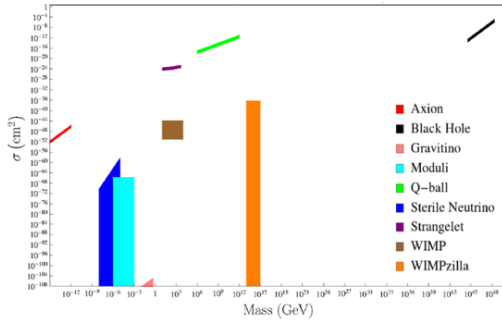


Figure 5: Candidates for DM in the 2D plane SM-DM cross-section (cm^2) vs DM mass (GeV). The phase space favoured by theory for WIMPs is shown with the brown rectangle and correspond to the red box of Figure 6.

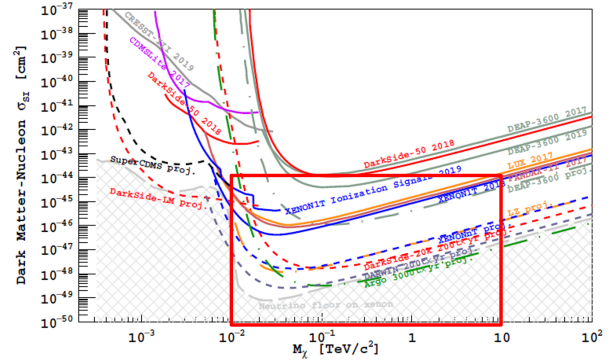


Figure 6: Exclusion curves from WIMPs direct detection experiments with dual phase TPC, in 2D plane SM-DM cross-section (cm^2) vs DM Mass (TeV/c^2). The full lines are the published results (<2023) and the dashed lines are projection for future experiments (>2025).

As shown in Figure 5, the phase space for DM candidates covers almost 60 orders of magnitude for the mass and 108 for the cross-section. These various candidate masses could go from 10^{-15} GeV (Axions) to 10^{49} GeV (Black-Holes). Among these candidates, we will focus on the WIMP, since it is one of the best motivated. Indeed, in the SM, there are large radiative corrections for the Higgs boson mass when energy is increasing. This calls for new particles to cancel these radiative corrections. The physics of the SM must be invariant under general transformations (translation, rotation, and boost) in the 4D space. The only way to extend this group of transformations is to postulate a new symmetry (SUSY) which will come with new particles (SUSY Particles), “symmetric” to the SM particles but with a new quantum number ($R_p = 1$ for SUSY and $R_p = -1$ for SM particles). SUSY particles partially cancel the radiative corrections of the Higgs boson, and the lightest particle from the SUSY should have all the properties of DM mentioned above, especially it is long-lived since R_p cannot be violated. This is therefore a very nice Weakly Interacting Massive Particles (WIMPs) particle, and the brown area on Figure 5 comes from this theory.

However, having 8 orders of magnitude for cross-section (from 10^{-44} to 10^{-52} cm^2) of the theoretical WIMPs and 4 for mass (from 10 GeV to 10 TeV) represents a huge experimental challenge. As shown in Figure 4, there are 3 way to detect DM (χ) :

- When two SM particles interact (red arrow), they create two WIMPs. This might happen in a particle collider like LHC.

- When two DM particles interact (blue arrow), they create two SM particles. From the measurement of the energy of both SM particles, it is possible to determine the mass of the WIMP particle. This is called indirect detection.
- When a DM particle interact with a SM particle (green arrow), they scatter and a recoil energy can be measured on the SM particle. This is called the direct detection.

The DarkSide-20k experiment is only sensitive to the direct detection of WIMP. The idea is that the halo of Dark Matter of the Milky Way has a density of $O(0.1) \text{ GeV/cm}^3$ and move at 250 km/s with reference to Earth. However, the weak interaction between DM and SM particles makes it very difficult to detect WIMP : for one ton of Argon, it takes one year to detect 1 event if $\sigma = 10^{-45} \text{ cm}^2$.

Several experiments based on different technologies have already tried to detect WIMPs. Figure 6 shows that the experiments with Time Projection Chamber (TPC) filled with Liquid Xenon (LXe) or Liquid Argon (LAr) are the most sensitive and will remain the most sensitive in the decade to come. Experiments that use LXe reach the lowest cross-section ($\sim 5 \cdot 10^{-47} \text{ cm}^2$ at 20 GeV). Indeed, Argon based TPC face limitations with ^{39}Ar contamination. However, these LAr TPC experiments get better results with lower masses (because the Ar atom is lighter than Xe)². Note that newer generations as DarkSide-20k should be able to reach cross-sections of 10^{-48} cm^2 around 100 GeV.

1.2 DarkSide-20k experiment

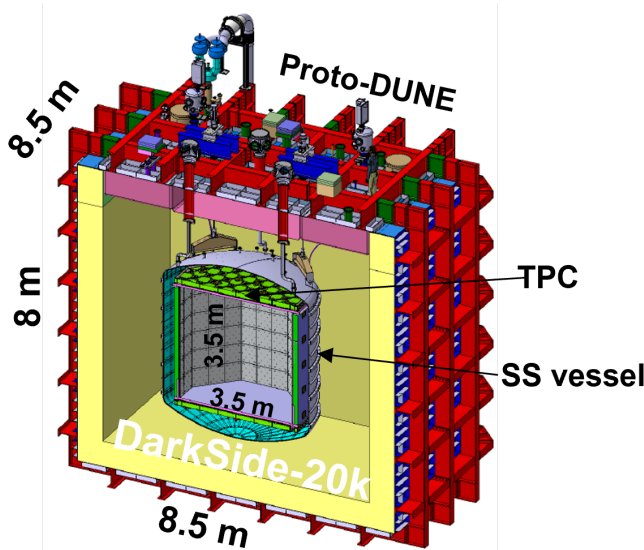


Figure 7: Proto-Dune where DarkSide-20k TPC will be placed.

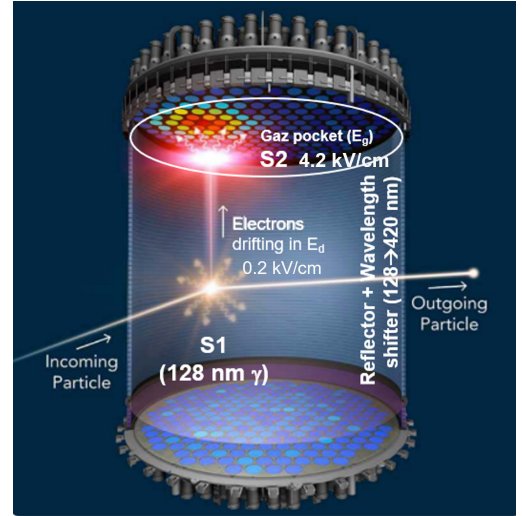


Figure 8: LAr dual phase TPC, with the scattering of an incoming particle on an Ar atom.

DarkSide-20k (DS-20k) is an international experiment whose main goal is to discover DM if made of WIMPs. The experiment will be at the National Laboratory of Gran Sasso (LNGS), under 1400 m of rock to avoid cosmic rays, and will be placed inside a Proto-Dune detector ($8.5 \text{ m} \times 8.5 \text{ m} \times 8.5 \text{ m} = 614 \text{ m}^3$, see Figure 7). The TPC is filled with 50 tons of purified Liquid Argon (LAr), and the veto (a LAr shield to tag the neutrons) is made of 30 t in between the TPC and the Stainless Steel (SS)

²It is important to have LAr and LXe experiments looking at the same phase space to be able to guarantee the existence of WIMP if a detection is positive.

vessel. Out of the SS vessel, 700 t of atmospheric argon are present in the outer layer of Proto-Dune (inner yellow part on the Figure 7).

1.2.1 Liquid Argon Dual Phase TPC

DS-20k relies on the purified LAr dual-phase TPC technology, shown in Figure 8. A dual phase TPC contains mainly LAr and a small gas pocket at the top. When a particle collide with an Ar atom, the atom is excited and emits photons of 128 nm (S1, scintillation signal) or valence electrons that are drifted to the gas pocket with an electric field of 200 V/cm (S2, ionization signal). Photons will then be reflected, and wavelength-shifted to 420 nm thanks to mirrors and tetraphenyl butadiene present on the walls, and will be detected by Silicon Photo Multiplier (SiPM) modules placed at the bottom and the top of the TPC.

Two type of interactions can happen in the TPC, a Nuclear Recoil (NR), and a Electronic Recoil (ER). The interaction of a neutron or a WIMP with an LAr atom is a NR, which produces many scintillation photons and few electrons. S1 is dominated by a fast signal (6 ns). The interaction of a electron or a photon with an LAr atom is a ER and will produce a slow S1 (1600 ns) but more electron with respect to NR (S2 will be greater). Therefore, ER and NR signals are different in many aspects ($S2/S1^{ER} \gg S2/S1^{NR}$, S1 slow vs S1 fast).

Getting both signals S1 and S2 allows to very precisely measure the energy left by the incoming particle and the coordinates of the collision, and therefore what particle reacted with the TPC. However, to be able to know that, a TPC response calibration is needed with radioactive sources, where energy is known.

1.2.2 Challenges of DarkSide-20k calibration

To be able to detect and analyse a signal produced in the TPC, a calibration of the SiPM response is needed. To do that, a radioactive source can be moved around the TPC (see Figure 9). When the source emits a radiation (photon, neutron, etc.), this radiation interacts with the Ar atom of the TPC and will be detected by the SiPM modules. Because the source position and the type of radiation it emits are known, the signal measured should correspond to the position and energy of the original source. My predecessor [3] worked on the signal reconstruction parameters needed to be sufficiently sensitive to a given signal, without having a huge background or noise.

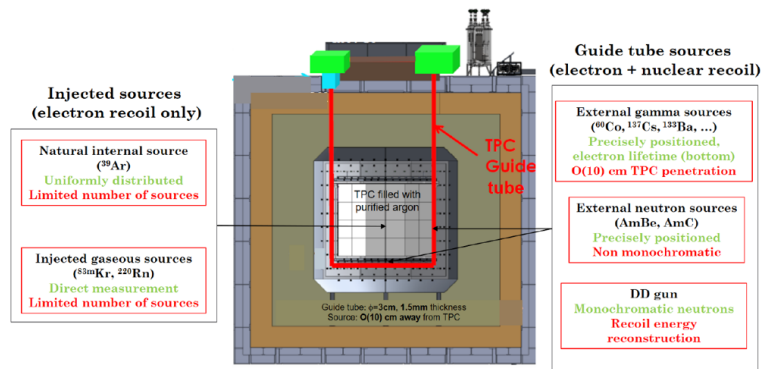


Figure 9: U-shaped guide tube system in the TPC and different radioactive sources.

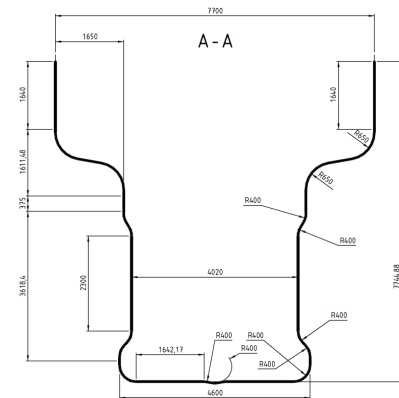


Figure 10: Sketch of the tube system.

Figure 10, shows the design of the TPC guide tube system. It is a 20 m long tube with 15 bends

in total, all of them having 40 cm diameter bending. The tube has an internal diameter of 3 cm with 1.5 mm thickness. Two of these tubes will be placed around the TPC inside the Proto-Dune cryostat. The source will stop at 9 positions. Simulations allowed to estimate the amount of time spent in a given position (see Table 1). Before constructing the final system, the robustness of the DS20k motors to move the sources need to be tested. Therefore, 3 Mock-ups have been built : one for testing the motorized system inside a 1:1 tube system at warm, and two testing the motorized system with short tube but at LN2 and LAr temperature (-186 °C).

Source	^{57}Co	^{133}Ba	^{22}Na	^{137}Cs	^{60}Co	AmBe	AmC	AmLi
Energy (keV)	122	356	511	662	1173	[0.2, 12]	[2, 7]	[0, 2]
Activity (side) (kBq)	18	1.9	0.36	2.2	0.36	0.14	0.15	-
Activity (bottom) (kBq)	100	5	0.67	4.6	0.6	0.18	0.18	-
Duration of calibration (h)	3.84	18.72	23.52	36	74.4	200	200	-
Time on each spot	12'	1h50'	2h20'	3h45'	8h	22h	22h	-

Table 1: Simulation of TPC table. The activity of each source in kiloBecquerel impact the duration the source need to stay at each spot in the tube during the calibration process.

1.3 Long run Mock-up calibration at LAr and LN2 temperatures

My work consisted in running the Mock-up placed at CERN's Cryolab, during one month at LAr and LN2.

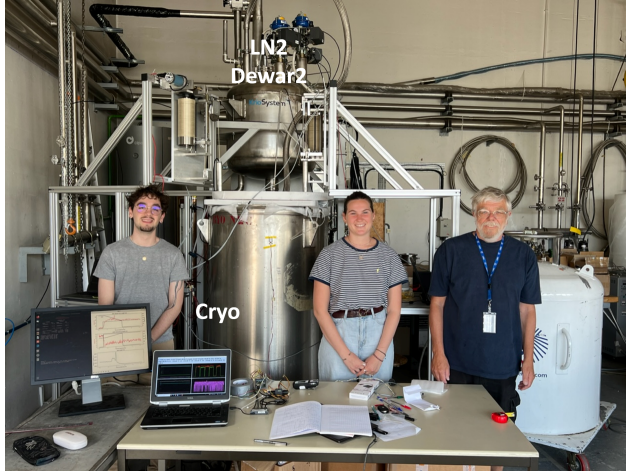


Figure 11: Picture of the Mock-up at CERN's Cryolab. From left to right : Lucas Boistay (CERN), Marie Van Uffelen (CPPM), Peter Skensved (Queen's University)

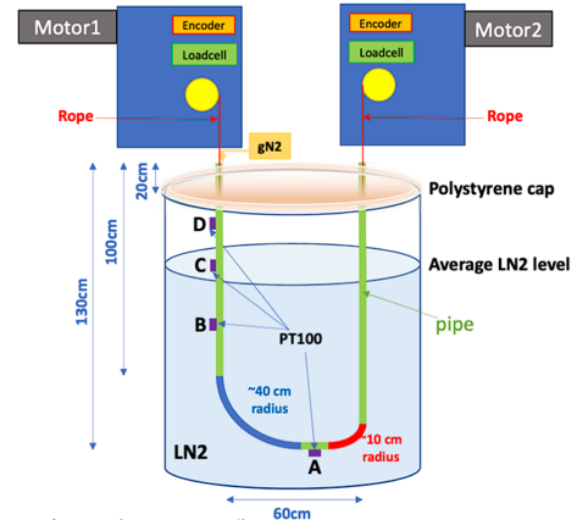


Figure 12: Mock-up explanation with the motorized system.

As Figure 11 and 12 show, the Mock-up is composed of a tank that will be filled with LN2 or LAr, 2 motors, DarkSide-2 (DS2) on the left side and DarkSide-4 (DS4) on the right side, a rope which a pseudo-source (Figure 13) will be attached on, and 4 positions named from D (top) to A (bottom) where PT100 temperature sensors have been placed. The tubes are closed with a plastic cap. It is not hermetic because there are holes to pass both the rope, and a pipe to flush liquid nitrogen gas (gN2) inside the tube to keep the humidity under control. The motorized systems (Figure 14) are

composed of a shaft coupling that pull the rope, a spring and pulleys to have a constant tension strength and a load cell. The length between the source and the motors can be precisely known by the shaft coupling and the encoder on the load cell.



Figure 13: Picture of the pseudo-source ($\Phi = 2.5$ cm, $L = 5.5$ cm, $M = O(100)$ g)

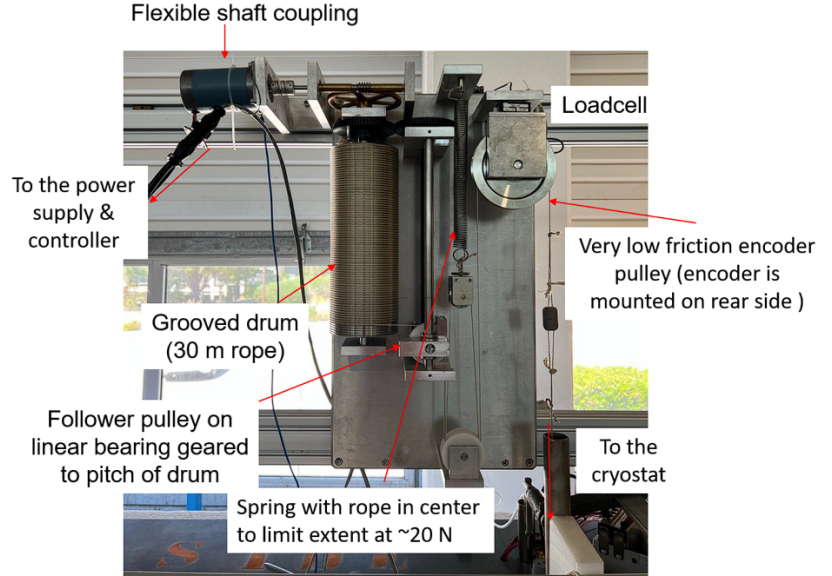


Figure 14: One motorized system explanation.

This Mock-up has for purpose to see how the source react when it is left for long periods of time (long-stay test) corresponding to Table 1, and check if the motors can stand intense wage, e.g. 35 back and forth in few hours (stress test).

Stability situation with the Mock-up is first discussed in section 1.3.1, then the LN2 tests and the LAr tests results are presented (section 1.3.2 and 1.3.3), and finally conclude on the extrapolation to DS-20k (section 1.4).

1.3.1 Reaching stability during LN2 tests

To collect and analyse information, a certain degree of stability within our system needs to be established. Temperature of PT100 probes and the level of liquid in the tank during LN2 tests is shown in Figure 15 and 16. Only the D sensor located close to the top as visible on Figure 12 goes from LN2 temperature to -100 °C, all other probes are still below LAr temperature during the whole time. This mean that almost all the tube is at cryogenic temperature.

On Figure 16, the gN2 flow that goes into the tube is shown as a function of time. This was meant to prevent the ice formation, but as Figure 17 shows, some ice still formed during the preparation phase. This is due to the presence of LN2 inside the tube (Figure 17 top on 10/06), implying that the flow of gN2 coming from the left side cannot go into the right side of the tube. The ice formation is then increasing during the night. On day 13/06, a T shaped pipe was added to flush gN2 into both side of the tube. At the end of the day, the ice mitigated and transformed into soft frost. The situation stayed constant during the whole test period, as shown on the final day picture (26/06).

When stable conditions have been reached (13/06), the tests at LN2 temperature (18 days) and then on LAr (17 days) were performed.

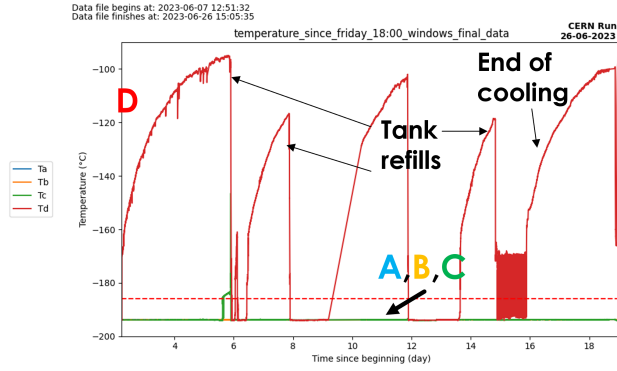


Figure 15: Temperature vs time for LN2.

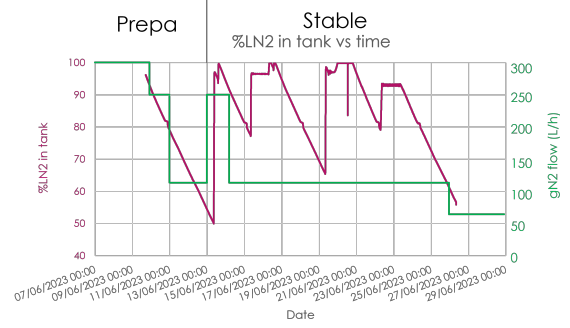


Figure 16: LN2% in tank (purple) and gN2 flow (green) vs date during LN2 tests.

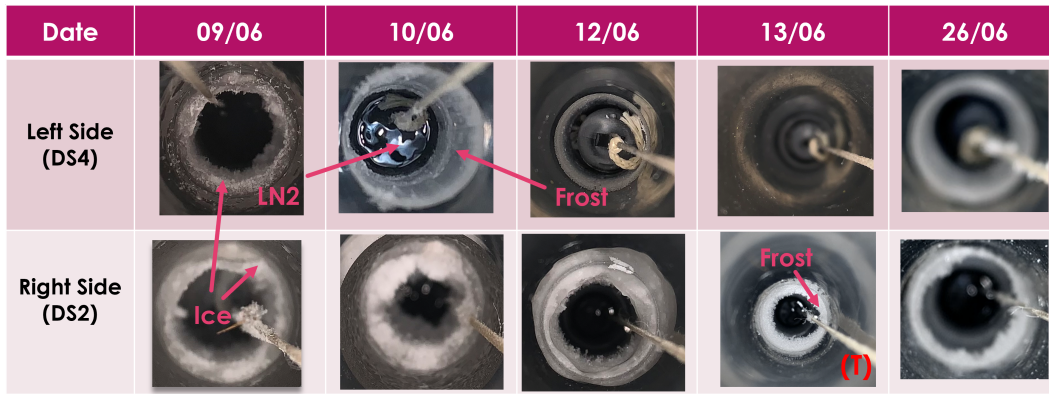


Figure 17: Ice formation during 17 days. Ice mitigation by gN2 flush (from ice to frost).

1.3.2 LN2 tests

Stress test to check the robustness of the motor system were carried on by doing 35 back and forth (b&f) per day from the cold garage (just above D) to A (so 1.3×2 m) with a 1 min stop at the edges, and this during 8 days. 280 b&f were made, which is 70 times DS-20k for a total length of ~ 740 m, which is 5 times DS-20k. Figure 18 shows that in average the tension is stable, with a 23 N tension for DS2 and 16 N tension for DS4. This tension difference can be explained from the geometry of the Mock-up. Indeed, the source is always closer to DS4, and the DS2 motor have to pull more length, which increases the tension. When the motor is not pulling (it follows the other motor), the tension is always around 6 N. Overall, tension is between 15 and 30 N, with small variations depending on the day.

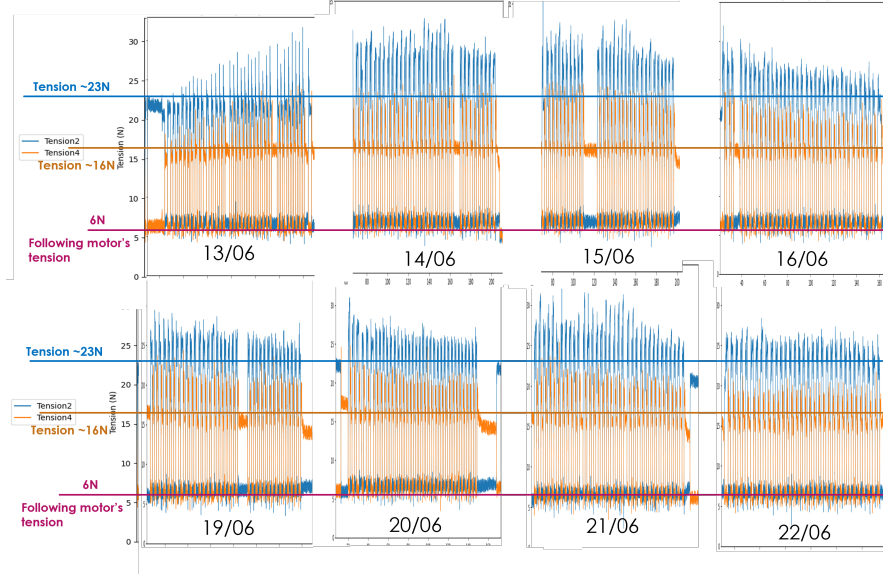


Figure 18: Tension vs time during stress test with LN2.

The second test check for the tension value when the source is left at a specific position for a long time, as foreseen in DS-20K (Table 1). The values taken are 1 min, 10 min, 30 min, 1h ... up-to a whole weekend. Then the source is moved again and get the maximum tension value during the movement. Figure 19 shows that the duration of the stay on the same position and the maximum tension value are not related.

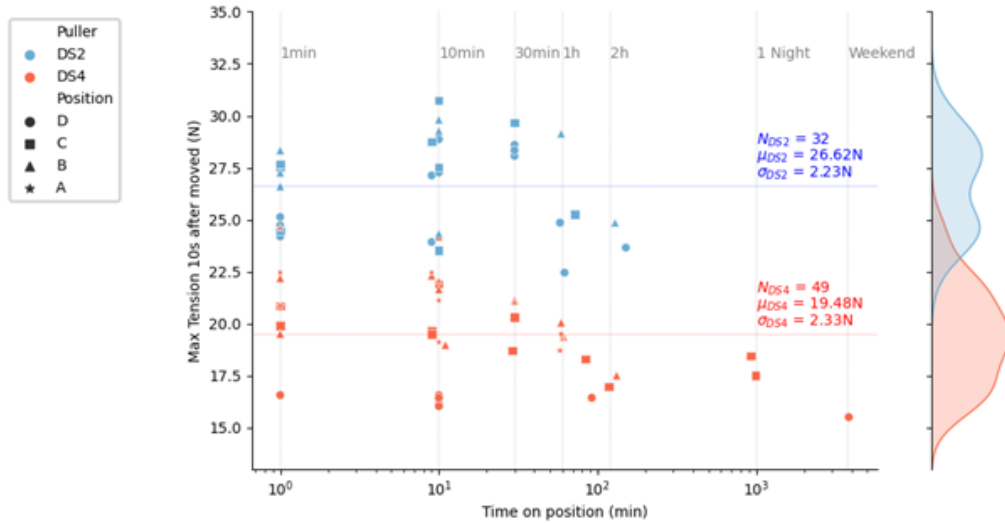


Figure 19: Max tension in the 30 s following the motion from a position vs staying duration during long-stay tests. 32 DS2 points (blue), 49 DS4 points (red).

1.3.3 LAr tests

The same Mock-up was run at LAr temperature. No autofilling was possible, and the tank was filled up to 60%. However, because LAr has a lower liquefaction temperature, the tank was able to stay filled for a longer amount of time. Because the temperature is lower than LN2 temperature, no LN2 was seen inside the tube. This allows gN2 flushing to flow in the totality of the tube to prevent humidity. Stability was reached very rapidly in those conditions.

Humidity was brought by blowing into the tube (100% humidity). Needless to say, this is an impossible situation. The final design is equipped of glove-box, that prevent any humidity in the tube. Figure 20 shows that there is a threshold value for gN2 flushing that allow humidity to decrease “instantly” (≤ 5 min). Depending on whether the source is at D or A position, the threshold value will be different (resp. 100 and 150 L/h). By assuming the same scaling, the threshold value for DarkSide-20k with the source at the bottom (worst-case) might be around 300 L/h.

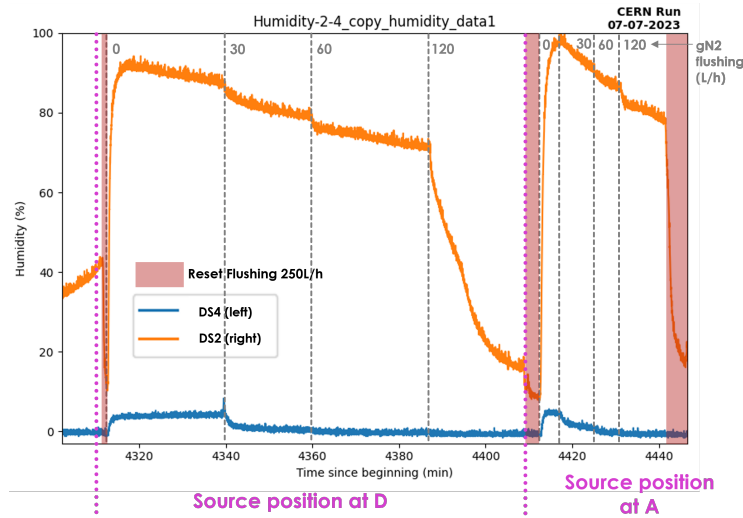


Figure 20: % of Humidity vs time for different gN2 flush.

With the lack of LN2 inside the tube and a 100% humidity, ice was visible from the top of the tube. After gN2 flushing, this ice turns into soft frost. But this frost might still have an effect on the tension. Stress tests and stay tests were run. Figure 21 and 22 show that the average tension on the stress test and long stay test are similar to the LN2 tests. Frost has no significative impact on the tension.

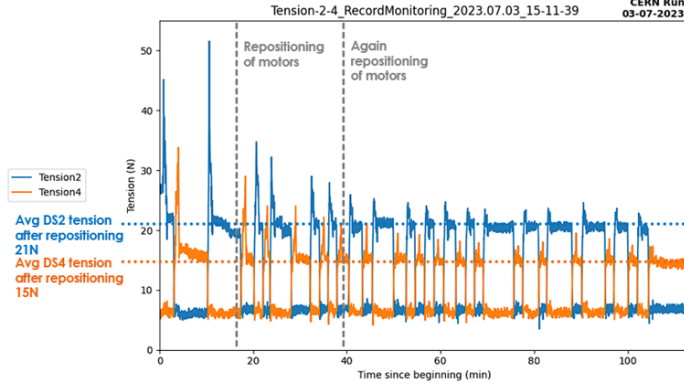


Figure 21: Tension of motors vs time during stress test. Two repositioning of motors during the test was needed because the rope was rubbing against the border of the tube's caps.

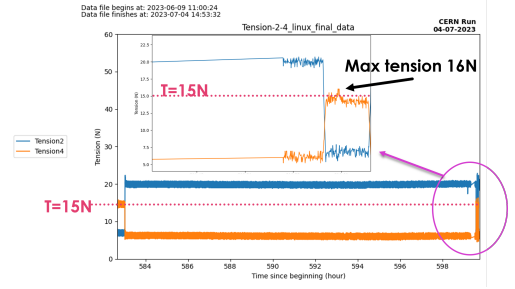


Figure 22: Tension of motors vs time after long stay test for one night. Same plot when source stays for 5 days at the same position.

1.4 Extrapolation to DS-20k

Table 2 shows the performance values extracted from LN2 and LAr tests performed at CERN in terms of speed of the source, position accuracy, tension, ice formation ... The right column gives the DS-20k specifications that are all met with the Mock-ups, giving confidence in the DS-20k design.

	CERN Mock Up		DS-20k
Temperature	LN2	LAr	LAr
Number of days	18	14	30
Speed of the source (cm/s)	1	1	≥ 1
Position accuracy (cm)	± 1	± 1	± 1
Tension (N)	15-30	15-30	< 150
Ice formation (block)	Mitigated with gN2	None	No
Total length for one source (m)	740	> 100	160 (/yr)
Total number of b&f / pipe	280	35	4 (/yr)

Table 2: Mock-up results compared to design specifications for DS-20k.

2 Proto-DUNE

2.1 Neutrinos and DUNE experiment

2.1.1 Neutrinos

The neutrino is an elementary particle of the SM as seen in section 1.1.1. His existence was supposed in 1930 by Wolfgang Pauli and was discovered in 1956 by Frederick Reines et Clyde Cowan. The neutrino has a “flavour” that gives 3 different leptons : the electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). Another experiment at Super-Kamiokande detector in 1998 found that neutrinos oscillate. Indeed, a neutrino emitted is not in an eigenstate of the Hamiltonian. It’s in a superposition of ν_1, ν_2 , and ν_3 which are the eigenstate of Hamiltonian.

However, because neutrinos have no electric charge, nor colour, they don’t interact through respectively electromagnetism and strong force. It seems like they only interact through the weak force³. For 10 billion 1 MeV neutrinos going through Earth, only one will interact with an atom, but the cross-section increase with higher energies.

After the Super-Kamiokande experiment, further studies reinforced the idea of neutrino oscillations. These oscillations are governed by a set of parameters: the two squared mass differences $|\Delta m_{21}^2|$ and $|\Delta m_{31}^2|$, and the elements of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) mixing matrix, which are the mixing angles and a phase. The probability of a neutrino changing its flavour during propagation can be expressed in terms of these parameters, and it’s this probability that has been studied in various experiments [4], using both natural sources of neutrinos (like the sun or atmosphere) and man-made sources (reactors or particle accelerators).

Charge-Parity (CP) violation for the lepton sector might be discovered from comparing the differences in oscillation pattern of neutrinos and anti-neutrinos (if the PMNS phase is not 0).

2.1.2 Dune experiment

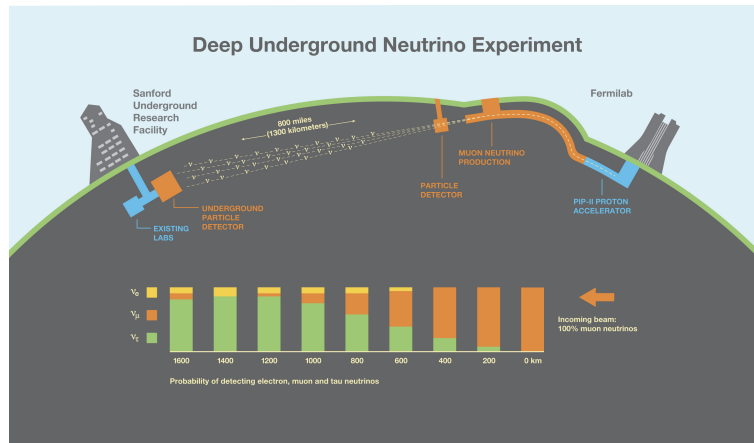


Figure 23: DUNE Experiment : the neutrino beam is sent from Fermilab over 1300 km to the far detectors.

The Deep Underground Neutrino Experiment (DUNE) will be a world-class neutrino observatory

³It seems like neutrinos might have interaction through gravity, depending on their masses.

and nucleon decay detector⁴.

The DUNE experiment is an international project and will be hosted by the U.S. Department of Energy's Fermilab. The experiment, as visible on Figure 23, will consist of a far detector located about 1.5 km below Earth surface at the Sanford Underground Research Facility (SURF) in South Dakota, at a distance of 1300 km from Fermilab world's most intense neutrino beam (neutrino $O(\text{GeV})$). Because neutrinos have such low interaction with matter, the beam will be able to go 1300 km through Earth crust to arrive at SURF. The SURF detector (see Figure 24) is a LAr-TPC with total mass for the 4 detectors of nearly 70 kilotons of ultrapure LAr. This LAr-TPC, as different from the DS-20k TPC, will make it possible to reconstruct neutrino interactions with image-like precision, as seen in section 1.2.1.

Deep Underground Neutrino Experiment
One of four detector modules in South Dakota

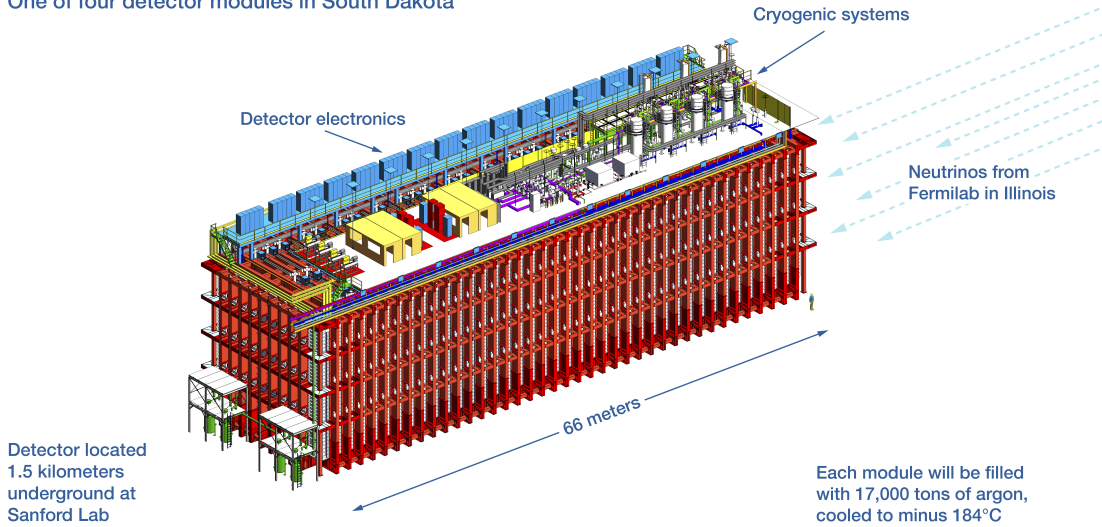


Figure 24: DUNE module.

The main goals of DUNE are :

- The neutrino oscillation measurements of ν_μ and $\bar{\nu}_\mu$ beams from Fermilab measure directly the CP violation, and the value of hierarchy of neutrinos might help to improve the knowledge on CP violation.
- Search for a proton decay (matter instability) that would prove the existence of physics beyond the SM.
- Measure the ν fluxes of a core-collapsing supernovae from our galaxy. This might give information about the early stages of supernovae formation, and birth of black-holes.

2.1.3 ProtoDune at CERN

ProtoDUNE [6] is a prototype of the DUNE experiment, located at CERN, and is primarily designed to validate the Liquid Argon Time Projection Chamber (LAr-TPC) technology for large underground

⁴Further details regarding DUNE can be obtained from the Far Detector Technical Design Report [5], however, a brief presentation will be presented here.

detector applications. The ProtoDUNE experiment has been designed to replicate as closely as possible the conditions and challenges that the DUNE experiment will face.

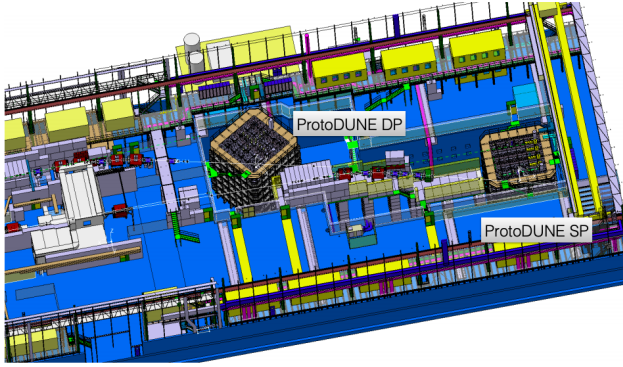


Figure 25: Plan of the Neutrino Laboratory at CERN.

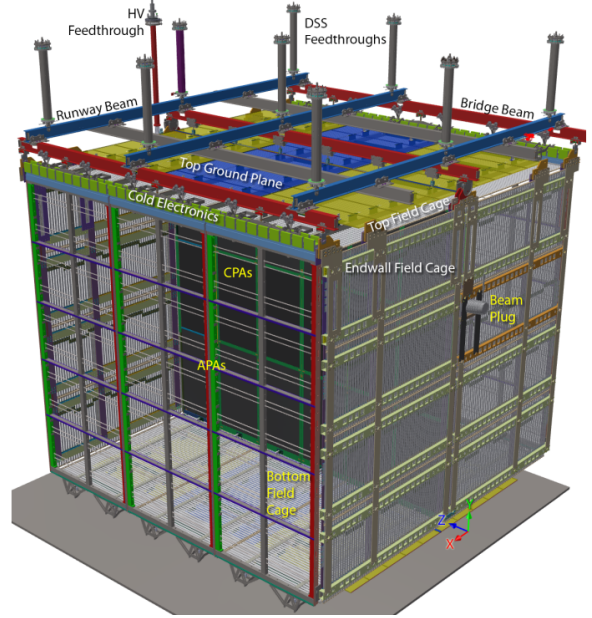


Figure 26: ProtoDUNE SP Mock-Up sketch.

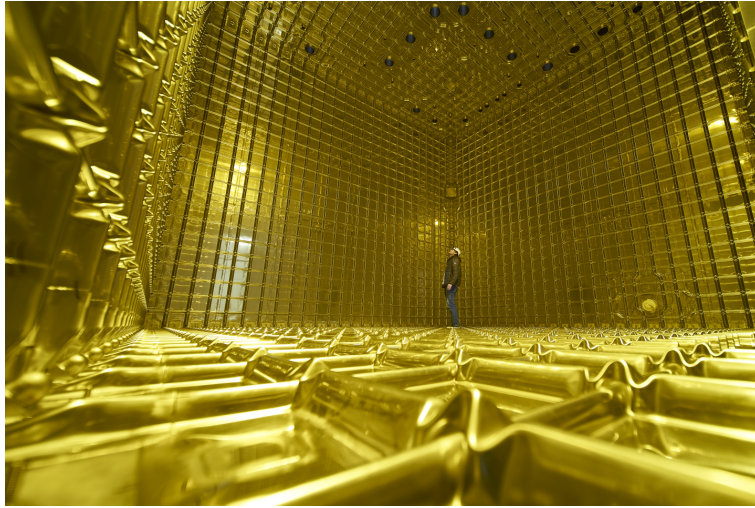


Figure 27: ProtoDUNE SP Mock-Up picture inside the TPC.

As visible in Figure 25, this facility is composed of 2 detectors : NP04 which is a single phase (SP) LAr-TPC with horizontal electric drift, and NP02, a SP LAr-TPC with vertical drift. Due to technological drawbacks, the NP02 Dual Phase was put aside for possible future improvement.

The NP04 (see Figure 26) is a 770 LAr tons SP TPC with a vertical drift of 500 V/cm. It will be exposed to the H4 beam composed of e , $K^\pm$, μ , p , $\pi^\pm$, and can also take cosmic ray data. When one of these particles interact with a LAr atom, electrons will be formed by ionization and will drift to 3 planes of wires : two induction planes (I1 and I2) and a collection plane where the electron

will be collected. A current will be detected on each strip when an electron moves through a plane. The charge deposition on these strips will then be analysed to reconstruct the track of the particle. NP02 is similar, with wires replaced by perforated PCBs and the drift is vertical.

Absolute energy scale calibration needs to be very precise due to the requirements of CP violation search. Several calibration technologies have been proposed for the DUNE detector, one of which relies on the use of monochromatic 1 MeV electrons produced by a Bismuth source to calibrate the gain of the readout system in the energy range of minimum ionizing particles. All these strategies will be implemented in NP02 and NP04, but the Bismuth calibration is being validating firstly in a dedicated smaller scaled detector, the 50 L LAr-TPC. This is the work I was involved in.

2.1.4 50 L LAr-TPC setup

The 50 L LAr-TPC setup visible on Figure 28 is a CERN prototype, having the same proportions of the final ProtoDUNE experiment. In these conditions, it's possible to analyse the data and prepare algorithms and tools.

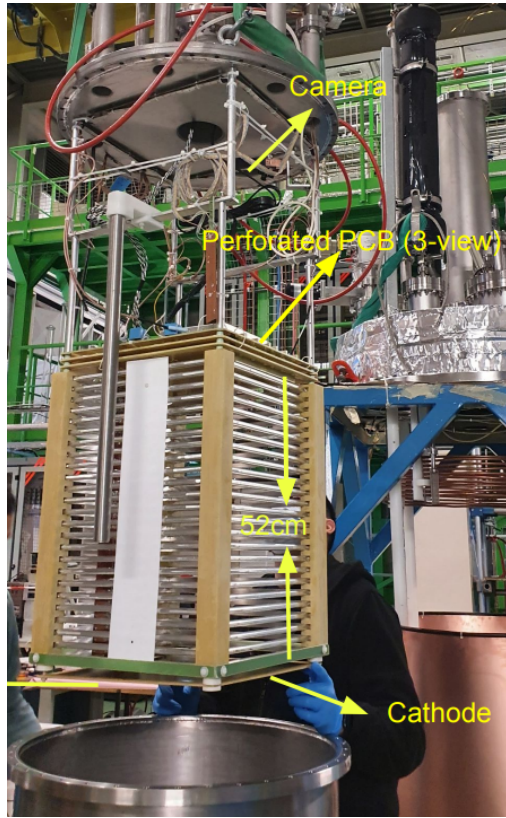


Figure 28: Picture of the 50 L mock-up.

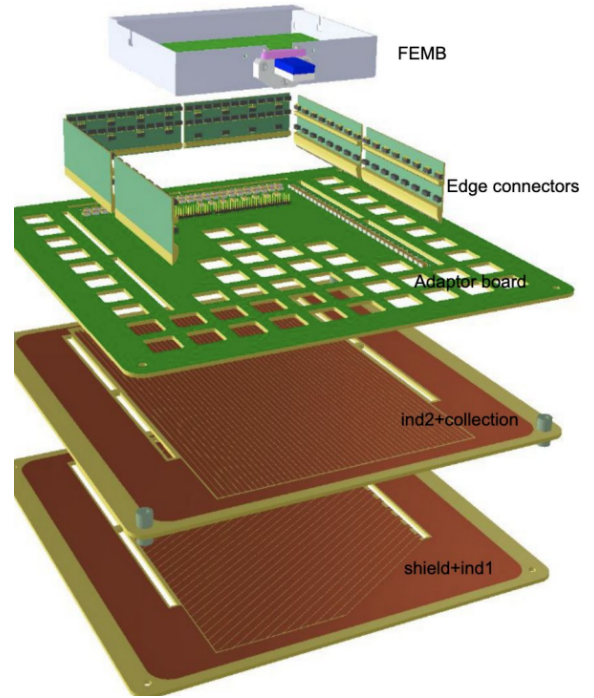


Figure 29: Top part of the TPC : Shield + 2 induction + collection planes on the first two PCBs.

Composed of a 50 L LAr-TPC with a cathode on the bottom and an anode on the top, this facility has a 52 cm height with a drift velocity of $1.5 \text{ mm}/\mu\text{s}$ due to the 500 V/cm electric field, in which ionisation electron will drift. The top part includes two perforated PCBs containing a shield, the two inductions planes and the collection plane (see Figure 29). The PCBs are pierced with holes which form strips, with a 5 mm pitch for the collection strips (48 channels) and 7 mm for the induction strips (40 channels each). Each strip direction on a plane has a 60° angle strip relative to the previous plane (see Figure 30).

Several interactions might happen in the TPC, but for the purpose of this calibration, a selection is done on only two interactions :

- Two 5 mm diameter ^{207}Bi sources are placed inside the TPC at different positions (one near the cathode, the other near the anode). These sources emit 1 MeV electron in the active volume with a 1.5 Hz rate, but are acquired by random trigger (with a 1-3 Hz frequency).
- Atmospheric muons μ_{atm} selected with an external muon trigger are cross the TPC with a rate of 0.05 Hz (see Figure 31).

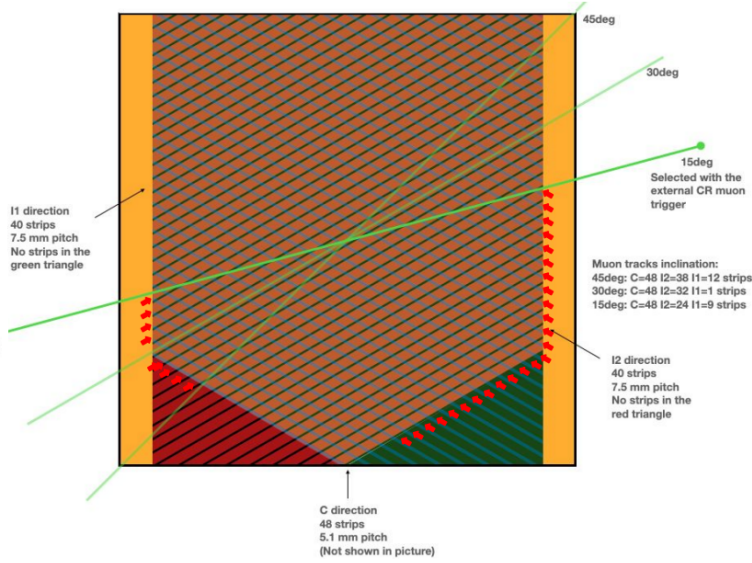


Figure 30: Top view with anode strips and muon track orientation.

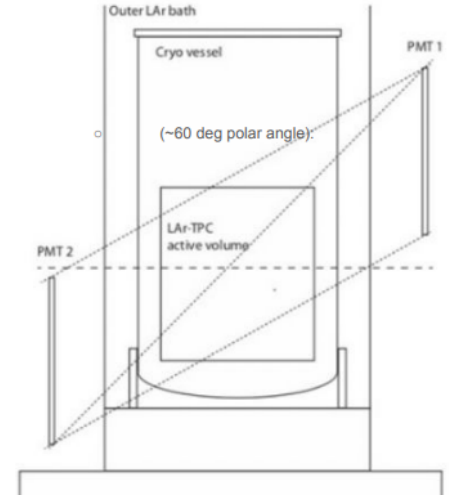


Figure 31: External muon trigger angle.

As explained in Section 2.1.3, it is possible to reconstruct the track of a particle from the data collected by the induction and collection planes. Moreover, from comparing the theoretical energy of emitted electrons of the ^{207}Bi sources with the data, the difference in energy peak give the LAr purity (as some oxygen and water might get into the TPC). Indeed, the charge deposited in the TPC will be lower for lower values of LAr purity.

However, to be able to compare these values, we need to be sure that every strip gives the same signal for the same deposited charge.

2.2 Cosmic muons analysis

A muon (μ) is a similar to electron elementary particle from the SM model (see Section 1.1.1). The μ has a -1 eV charge and a spin of $\frac{1}{2}$, but with a much larger mass ($\approx 207 \cdot m_e$). Cosmic muons are an indirect product of the proton decay in high atmosphere (see Figure 32). When a proton hits an atmospheric atom, it produces pions (π) which will decay rapidly into μ and ν_μ . The muon will then decay with a half lifetime around $2 \mu\text{s}$. With this lifetime, no muons should be detected on Earth surface, although due to relativistic speed (near c), the length from high atmosphere to the Earth surface is contracted and muons can be detected on very low altitudes.

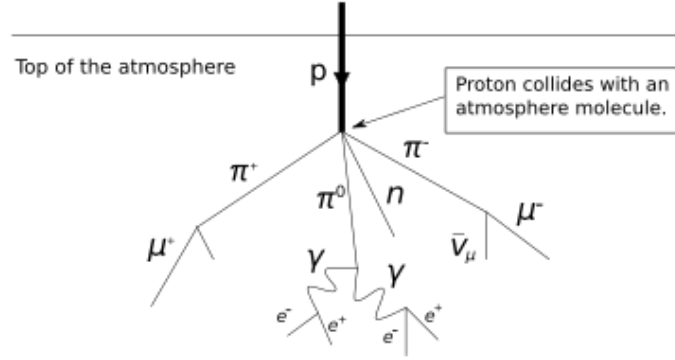


Figure 32: A primary cosmic particle collides with a molecule of atmosphere, creating an air shower. Muons are represented by μ^- and anti-muons by μ^+ .

As seen in the previous section, a data acquisition system (DAQ) is placed on the TPC to select 1 MeV muons and aim them with a certain angle inside the TPC. It will then be possible to reconstruct the track of the muon inside the TPC due to the formation of ionisation electron that will be detected by the planes.

2.2.1 Cosmic events

A previous work was done by my coworkers to transform the raw data and tag every source or cosmic muons events (see Figures 33 and 34)⁵. The data contains the value of deposited charge for every $0.5 \mu\text{s}$ on each strip, as shown in Figure 35. Strips from 1 to 48 are collection strips, 49 to 88 are induction 1 (I1) and 89 to 128 are induction 2 (I2). We can see on Figures 36 and 37 that peaks on I1 and I2 have a different shape from the collection strip. However, this is not an issue to get the total charge deposited in the strip.

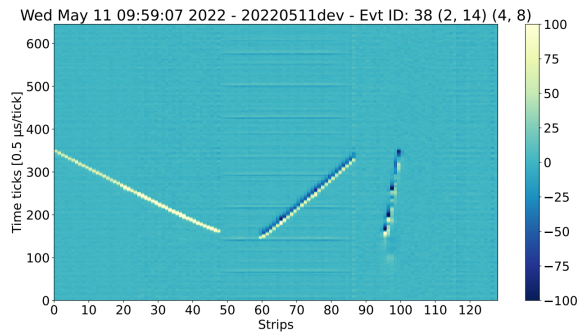


Figure 33: Muon track visible from the data on each strip.

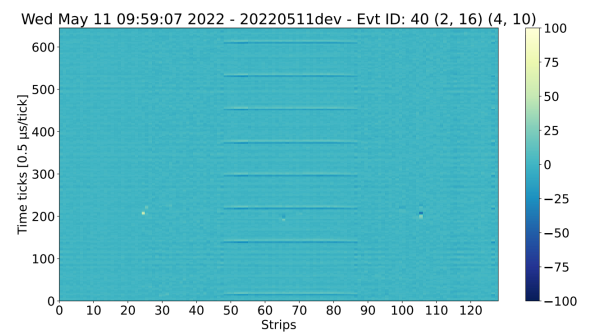


Figure 34: ^{207}Bi source visible (dot on collection and inductions) from the data on each strip.

However, every strip gives a different charge deposition value. This means a gain value need to be determined for each strip.

⁵There is a coherent noise of the I1 part (vertical lines), it is easy to removed with standard noise removal strategies.

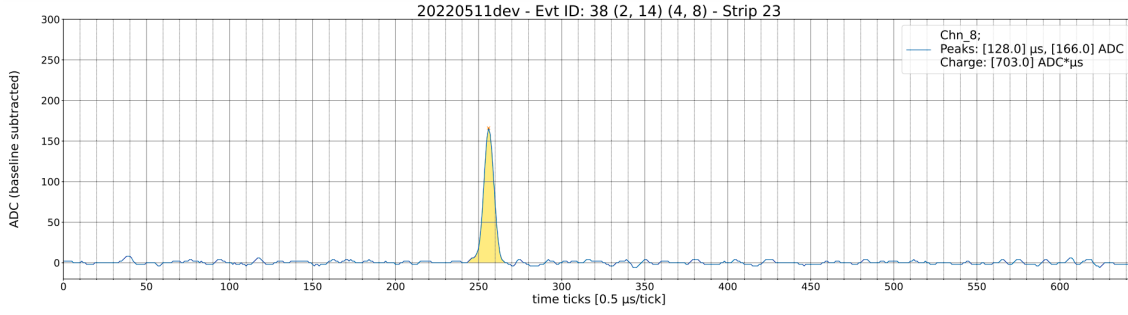


Figure 35: Deposited charge vs time for the strip 23 (collection). A peak is visible.

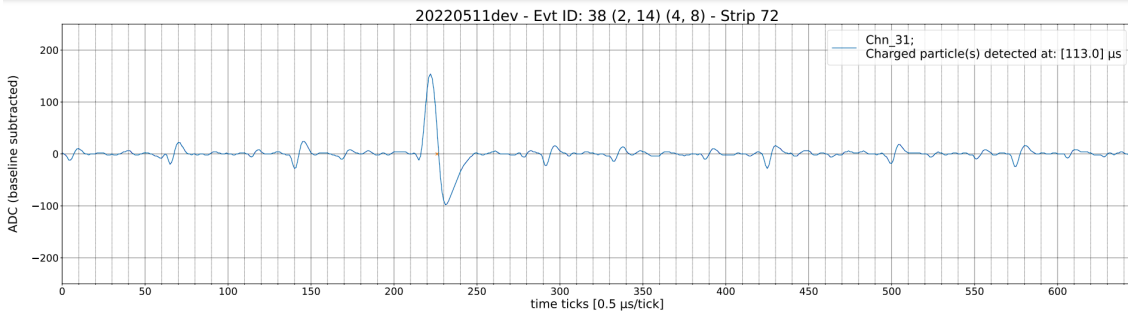


Figure 36: Deposited charge vs time for the strip 72 (Induction 1). A peak is visible.

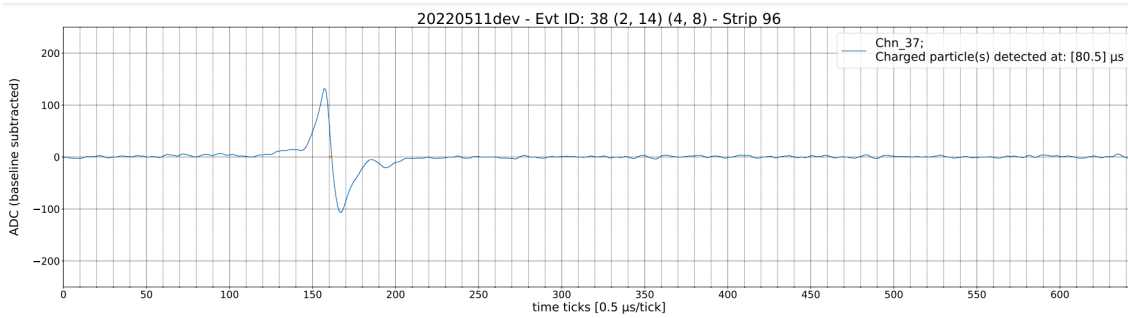


Figure 37: Deposited charge vs time for the strip 96 (induction 2). A peak is visible.

2.2.2 Event filtering

To be able to determine the charge deposition on each strip, each event needs to be filtered. Indeed, some cosmic muon event does not pass by every strip, which is needed to determine the gain, or the signal might be too blurry for later uses. The general filter is done by two separate ways :

- Passing by every strip filter : an algorithm detects if there is a peak on each strip.
- Number of straight lines : a Hough transform is applied to the image of the event to detect straight lines. If more than one line is detected on each part (Collection, I1, I2), it means this event is not trustworthy. Moreover, the slope of this line can be determined.

As visible in Figure 38, even if the track pass by every strip, it is possible to have a non-usable event. With these two filter, the reconstruction of the track is guaranteed.

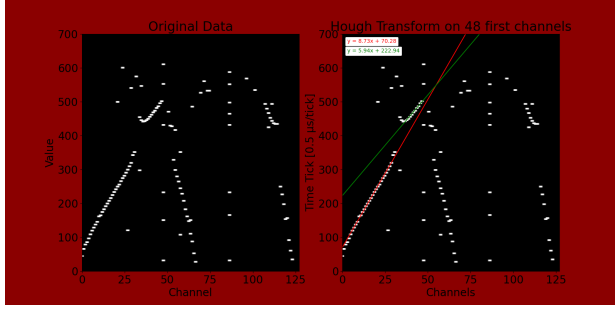


Figure 38: Example of a filtered event : on collection, the track is split in two, resulting two straight lines. The noise is not an issue because the Hough transform parameters are set for a highly visible line.

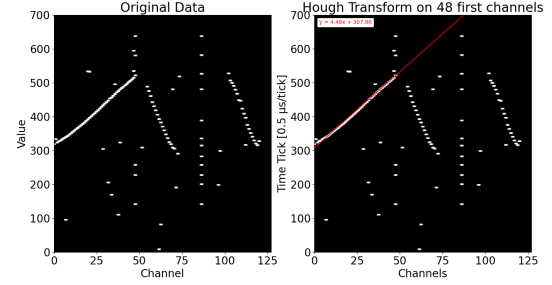


Figure 39: Example of a good event.

2.2.3 Charge deposition landau distribution

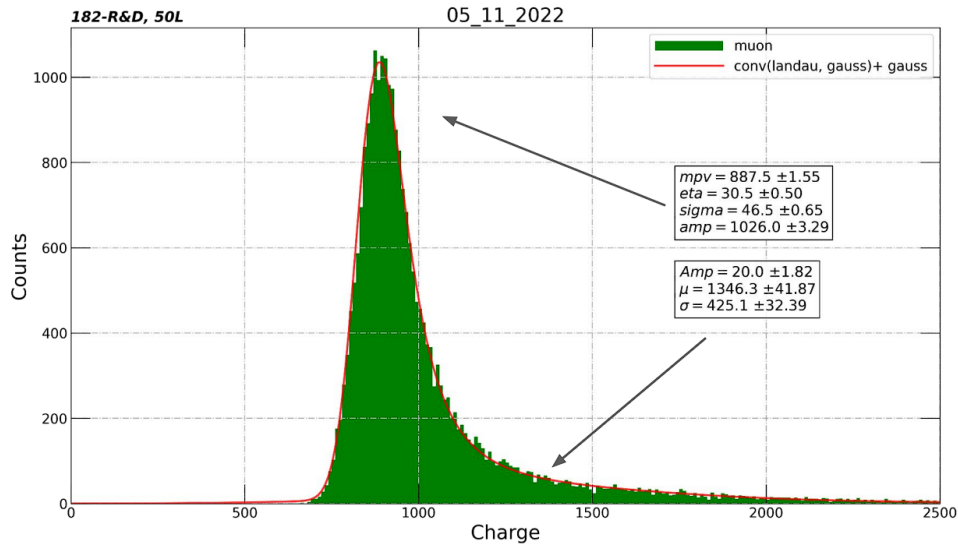


Figure 40: The landau distribution for the charge deposition in one strip (collection).

The final goal of this analysis is to know the final charge distribution on each strip to see if a gain is needed to normalise the charge deposition (for each strip to give the same value for the same amount of charge deposited). But one event is not sufficient for this analysis. The method found is to plot a distribution of the possible charge deposition values in each strip (see Figure 40). This gives a Landau curve, and the peak position of this distribution should be the same for each strip. However, because the track does not have the same exact angle for every event, each track does not deposit the same amount of charge. A reconstruction of the signal is needed to divide the amount of deposited charge by the length of the track before any normalisation.

Now that the slope of collection and (at least one) induction are found, the 3D reconstruction of the signal can be determined. Indeed, from the Figure 41, the ΔL formula for the length of the track is :

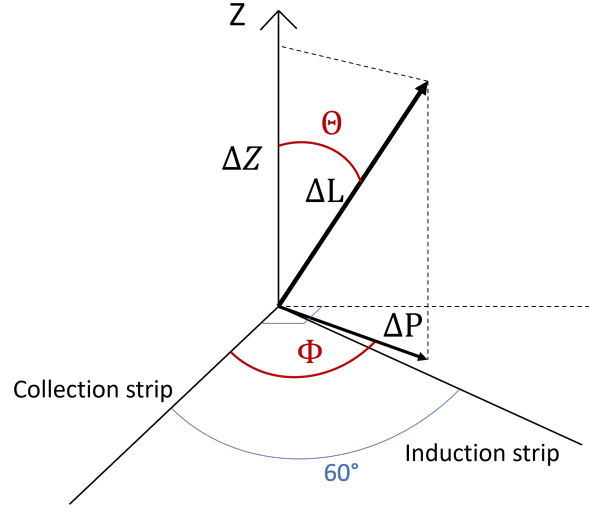


Figure 41: Geometric explanation for the reconstruction formula.

$$\Delta L = \sqrt{\Delta Z^2 + \frac{4}{3} \cdot (\Delta C^2 + \Delta I^2 - \Delta C \cdot \Delta I)} \quad (2)$$

with ΔI and ΔC the projection of ΔL on resp. induction and collection axis. Because we have S_C and S_I respectively the slope of the collection line and the slope of the induction line equals to :

$$S_C = \frac{\Delta C}{\Delta Z}$$

$$S_I = \frac{\Delta I}{\Delta Z}$$

equation 2 become :

$$\Delta L = \Delta Z \cdot \sqrt{1 + \frac{4}{3} \cdot (S_C^2 + S_I^2 - S_I \cdot S_C)} \quad (3)$$

and we can easily find θ the polar angle and ϕ the azimuthal angle :

$$\cos \phi = \frac{\Delta Z}{\Delta L} = \frac{1}{\sqrt{1 + \frac{4}{3} \cdot (S_C^2 + S_I^2 - S_I \cdot S_C)}}$$

$$\cos \theta = \frac{\Delta C}{\Delta P} = \frac{\Delta C}{\Delta Z \cdot \sqrt{\frac{4}{3} \cdot (S_C^2 + S_I^2 - S_I \cdot S_C)}}$$

The reconstruction of the track is now possible. Because muons are all arriving with almost the same angle inside the TPC, a distribution of the angles and of the track length would help to verify results.

Figure 42 shows that θ , ϕ and ΔL are around the same values. Another way to verify the results was to make the reconstruction with both I1 and I2 (when both signals were sufficiently clean). The results were very close, which suggests that our equation is correct.

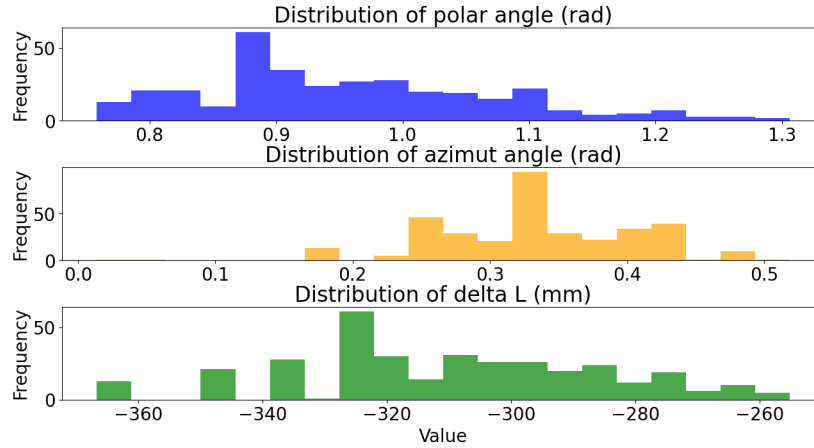


Figure 42: Angle and length distributions for θ , ϕ and ΔL . Distribution done on ≈ 1000 events (before filtering).

Due to time constraints, I couldn't finish this project, but the rest of it will be explained in the last section.

2.2.4 Normalisation

The charge deposited in each can be decorrelated to the muon track inside the TPC to obtain the normalised charge deposition following :

$$\tilde{C} = \frac{C}{\Delta L} \cdot 47 \quad (4)$$

with C the measured deposited charge. This new charge is divided by 47 because there are 48 strips (so 47 space between strips).

Now, the distributions are normalised by the particle track, and by checking the average value of the landau, a gain can be determined to have a general normalisation of each strip to counter the differences in the measures.

2.3 Conclusion

The ProtoDUNE experiment at CERN acts as a vital precursor for the ambitious DUNE project. DUNE aims to explore some of the most fascinating aspects of neutrinos, from their oscillation properties to potential sources of CP violation in the lepton sector, and the potential implications for the matter-antimatter asymmetry in the universe. The large-scale nature of DUNE, makes the need for a prototype even more urging. Some early results from T2K detector in Japan [7] seems to be sensitive to CP violation in the lepton sector⁶.

In conclusion, the ProtoDUNE experiment provides crucial insights and calibration data for the upcoming DUNE experiment. From the 50 L setup, the calibration of the DUNE experiment is already taking place.

⁶T2K is a way smaller detector with way less energetic neutrinos. These results were given with large uncertainties.

To conclude this report, I would like to thank CERN's Summer Student Program to let me take part of this incredible journey through world-class experimental physics. My involvement in both DarkSide-20k and DUNE enriched my comprehension of collaborative scientific research, emphasizing the importance of international teamwork.

I'm profoundly thankful to Pascal Pralavorio, not only for his expert guidance, but also for bringing to me work methodologies crucial for a recent bachelor's graduate. The insights and practices he shared will undoubtedly come with me throughout my academic journey. I also extend my appreciation to Marie Van Uffelen, Peter Skensved, and Pierre Barrillon for their invaluable feedback and support during my internship.

Additionally, my sincere gratitude goes to Francesco Pietropaolo and Mattia Fani. Their patient explanations of the theoretical aspects of the DUNE experiment were enlightening, as well as their assistance in data analysis, which was also vastly beneficial.

Lastly, my sincere thanks to the team behind the Summer Student Program for selecting me for this unique opportunity.

References

- [1] Salucci P. Corbelli E. The extended rotation curve and the Dark Matter halo of M33. *Monthly Notices of the Royal Astronomical Society*. 311, 2000. [Lien](#).
- [2] Jarosik N. et al. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results. *ApJS*, 192, 2011. [Lien](#).
- [3] Lecocq M. R&D on LAr-TPC for neutrinos and rare events. *CERN*, 2022. [Lien](#).
- [4] Abazajian K.N. et al. Cosmological and astrophysical neutrino mass measurements. *Astropart. Phys.* 35, 177, 2011. [Lien](#).
- [5] Dune collaboration. Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics. *Arxiv*, 2020. [Lien](#).
- [6] Dune collaboration. First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN neutrino platform. *Journal of Instrumentation*, 2020. [Lien](#).
- [7] The T2K Collaboration. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. *Nature*, 2022. [Lien](#).