3

The ProtoDUNE–SP Experiment

Contents

ProtoDUNE–SP is one of two prototypes for the DUNE far detector modules that has been operating at the Neutrino Platform at CERN since the summer of 2018. The experiment collected data from a charged particle beam for approximately 3 months before Long Shutdown 2 of the Large Hadron Collider. Since then a programme of cosmic ray data collection has been ongoing.

This chapter will outline the technical details of the ProtoDUNE–SP experiment. Section 3.1 will outline the role of ProtoDUNE–SP in the context of the DUNE experiment. This will be followed by a discussion of the main elements of the experiment, the ProtoDUNE–SP detector systems and the H4 beamline, in Sections

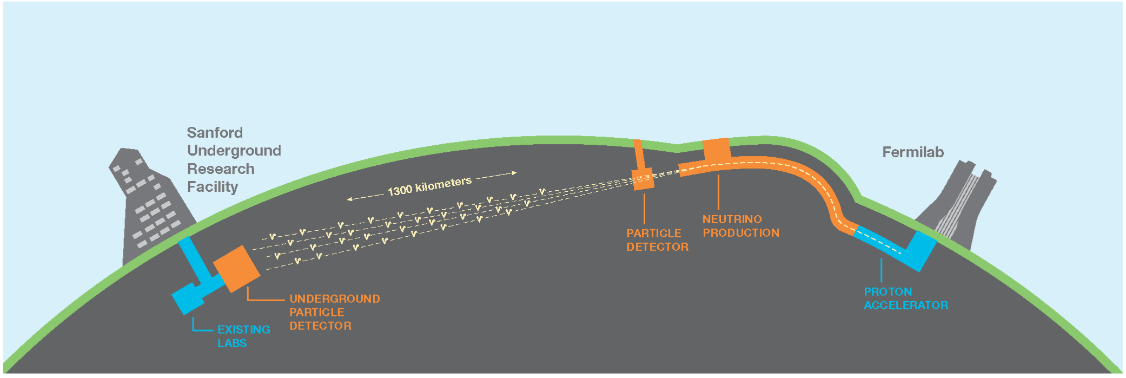


Figure 3.1: The Deep Underground Neutrino Experiment. Figure from [51].

3.2 and 3.3 respectively. The tagging of cosmic–ray muons for calibration is done by the Cosmic Ray Tagger which will be discussed in Section 3.4. Sections 3.6 and 3.7 will then discuss the simulation and reconstruction of ProtoDUNE–SP data. Finally Section 3.8 will cover details of the online monitoring system in ProtoDUNE–SP; as the primary developer and expert on the ProtoDUNE–SP online monitoring system during my time at CERN, the development and maintenance of this system represent a significant body of work over 12 months.

3.1 ProtoDUNE–SP in the Context of DUNE

The DUNE experiment will be a next generation neutrino physics and nucleon decay experiment consisting of three principal components; an intense broad band neutrino beam and precise near detector based at the Fermilab National Accelerator Laboratory near Chicago, and a far detector at Sanford Underground Research Facility in South Dakota, approximately 1300 km away from the neutrino source, as demonstrated in Figure 3.1. The DUNE experiment identifies three primary scientific goals [49]:

- Perform a comprehensive programme of neutrino oscillation measurements including measurements of δ_{CP}, neutrino mass ordering, and the θ_{23} octant.

- Search for proton decay in several decay modes.

- Measure ν_e from a core–collapse supernova if one occurs within our galaxy during the lifetime of the experiment.

In addition, the experiment hopes to fulfill a significant programme of secondary science goals:

- Other accelerator based neutrino physics, such as non–standard interactions, sterile neutrinos, and CPT violation.
- Measurements of neutrino properties using atmospheric neutrinos.
- Dark matter searches in both the near and far detectors.
- A programme of neutrino interaction physics studies in the DUNE near detector.

To achieve these goals DUNE has opted to base the near and far detector designs on the liquid argon time projection chamber (LArTPC) technology. The DUNE far detector will consist of four LArTPC detectors each with 10 kt of active liquid argon mass. This technology will have never before been used on this scale, and therefore, there has been a significant programme of LArTPC research and development ongoing to validate and characterise the performance of the technology for DUNE.

3.1.1 Liquid Argon Time Projection Chambers

A LArTPC consists of a large volume of highly–purified liquid argon immersed in an electric field. Charged particles traversing the liquid argon produce two primary energy depositions, a trail of ionisation electrons along their path, and prompt ultra–violet scintillation photons. After deposition the ionisation electrons drift in the electric field toward the charge readout plane where they induce electrical signals. Liquid argon is transparent to its own scintillation light and therefore the scintillation photons can travel through the argon to be collected in a photon detection system.The LArTPC detection principal is illustrated in Figure 3.2.

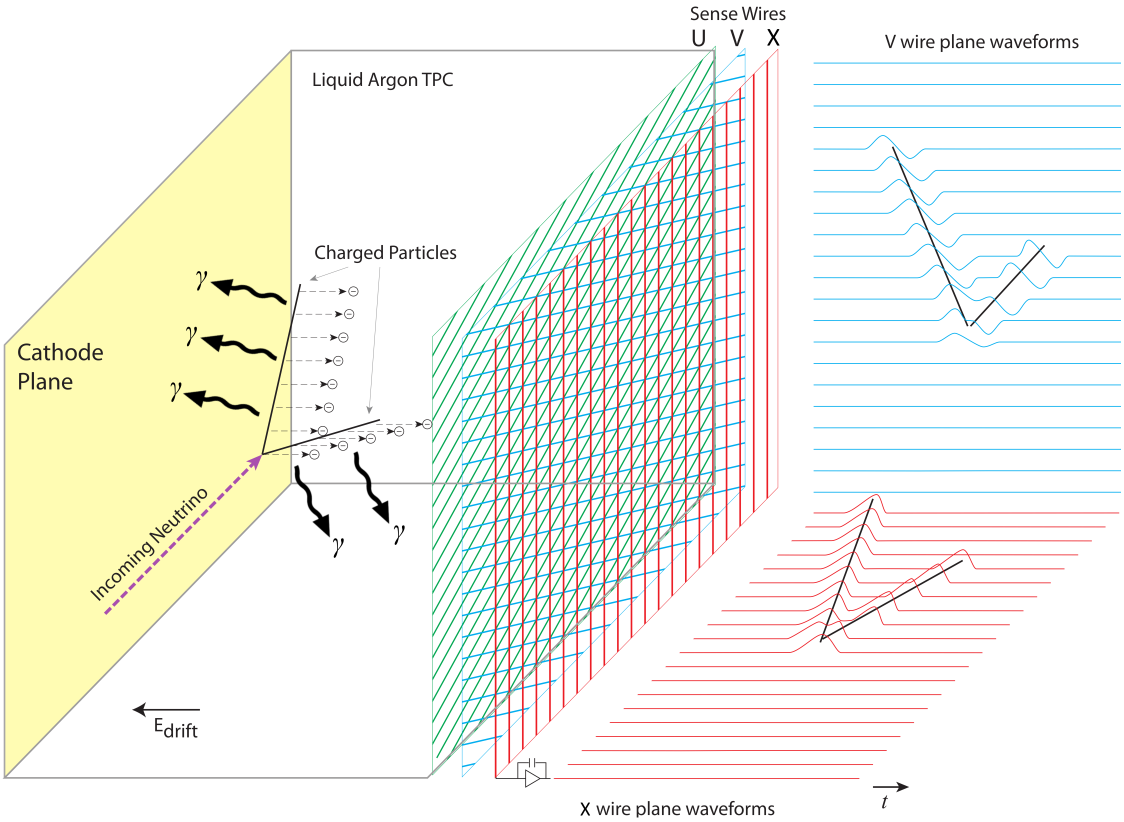


Figure 3.2: LArTPC detection principal. Figure from [52].

The Role of Light in LArTPCs

The ionisation signals in a LArTPC are slow, it takes charge milliseconds to travel from the cathode plane to the anode plane. In contrast, scintillation photons only take on the order of nanoseconds to reach the closest anode plane. This scintillation light plays an important role in the accurate 3D reconstruction of interactions in the LArTPC, it provides a t_0.

In a LArTPC interactions play out much quicker than the detector is able to record them; as such each event actually integrates over a large number of interactions within the readout window, analogous to taking a photograph with a long exposure. The true time, t_0, of the interactions in the event cannot be reconstructed from the ionisation signals alone; by utilising the much faster scintillation signals the time of interactions can be calculated with much higher precision, this data can then be used to correct the position offset caused in the ionisation signals.

The details of the charge readout and photon detection systems are specific to each detector, but broadly speaking LArTPC detectors can be split into two main categories: single–phase and dual–phase. In a single–phase detector the drifting ionisation electrons remain in the liquid argon and the signals are typically read out on three anode wire planes. A dual–phase LArTPC contains an additional region of gaseous argon in which a high electric field, known as the extraction field, is applied to extract the ionisation from the liquid before it is amplified and collected on a pair of anode wire planes [51].

ProtoDUNE–SP is one of two large scale prototypes for the DUNE far detector modules, which focusses on the single–phase LArTPC technology. The DUNE far detector modules feature a modular design in which each module is built up of a number of identical components, ProtoDUNE–SP was designed to prototype the design of many of these components at a 1:1 scale, including the anode planes, cathode plane, and photon detectors. The ProtoDUNE–SP experiment has four primary goals, as outlined in the Technical Design Report [53]:

- Prototype the production and installation procedures for the single–phase far detector design.
- Validate the design from the perspective of basic detector performance; this can be achieved with cosmic-ray data.
- Accumulate large samples of test-beam data to understand/calibrate the response of the detector to different particle species.
- Demonstrate the long-term operational stability of the detector as part of the risk mitigation program ahead of the construction of the first 10 kt far detector module.

As such, ProtoDUNE–SP represents a significant milestone in the development of the far detector for the DUNE experiment. Its successful operation, both in a test beam and with cosmic rays, provides valuable data with which to understand reconstruction and analysis of the data that will be collected by the DUNE far detector.

3.2 The ProtoDUNE–SP Detector

The ProtoDUNE–SP detector is located at the Neutrino Platform at CERN along the H4 beamline. It is a single–phase LArTPC detector with a total liquid argon mass of 0.77 kt, making it the largest monolithic single–phase liquid argon TPC to be built to date. The TPC comprises the following major components, which are illustrated in Figure 3.3:

- A cathode plane constructed of modular Cathode Plane Assemblies (CPA).
- Two anode planes constructed of modular Anode Plane Assemblies (APA).
- A photon detection system (PDS) which is integrated into the APAs.
- A field cage (FC), beam plug, and high voltage systems (HV).
- Readout electronics and Data Acquisition System (DAQ).

The detector components are designed to be an almost exact replica of the final single–phase far detector modules, but the detector has an overall scaling factor of approximately $1 : 20$ in terms of total liquid argon mass [53].

3.2.1 The Liquid Argon TPC

The ProtoDUNE–SP TPC has an active volume of 6 m (height) $\times$ 7.2 m (width, drift direction) $\times$ 7 m (length, approximate beam direction). The cathode plane at the center of the active width is flanked by two anode planes which define two 3.6 m drift volumes. The field cage around these two drift volumes helps to ensure a uniform electric field within the drift region.

Each anode plane is modularly constructed from three APAs which have dimensions 6 m (height) $\times$ 2.3 m (width). The APA frame holds three sets of parallel wires on the inward and outward facing sides, these are oriented at different

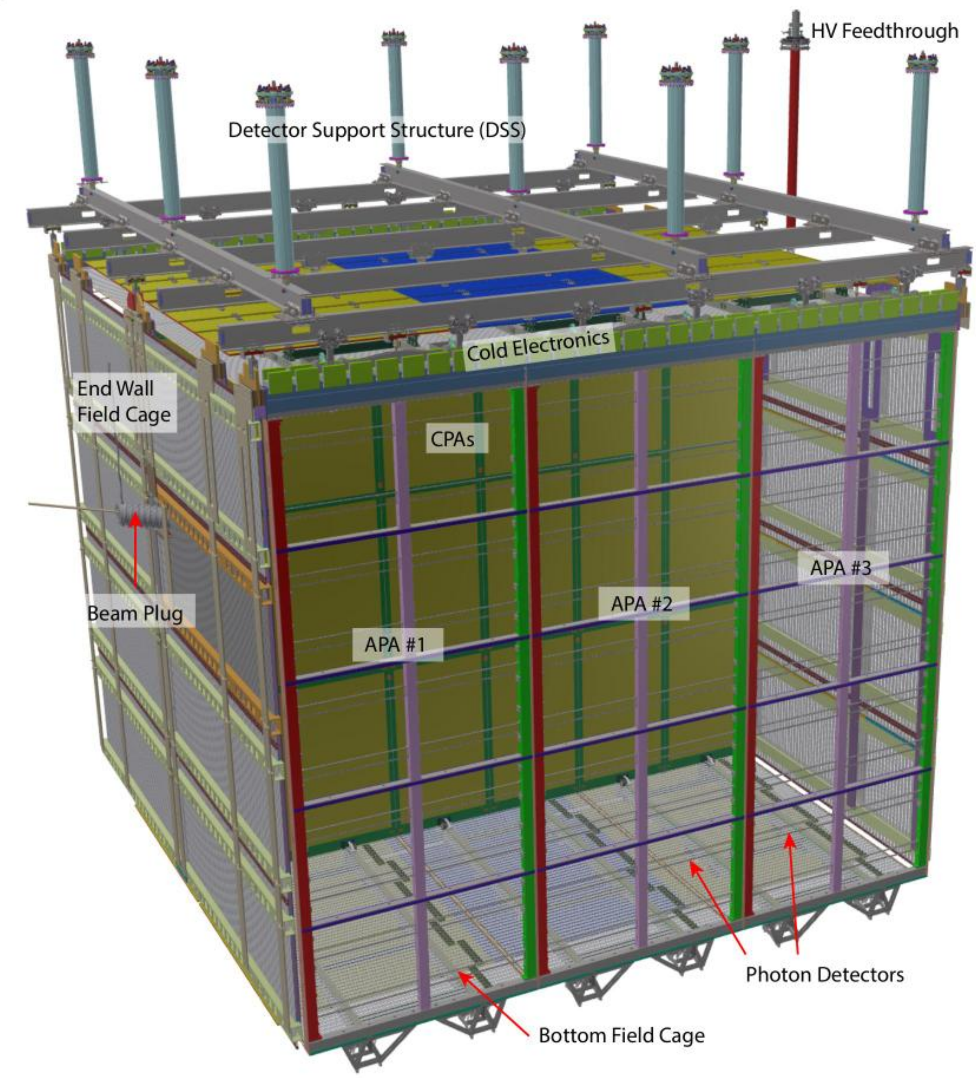


Figure 3.3: The main components of the ProtoDUNE–SP TPC. Figure from [53].

angles to enable 3D reconstruction. The outer two sets of wires are induction wires, these are electrically connected and biased such that they are electrically transparent to the drifting ionisation; ionisation passing the induction wires causes an induced bi–polar signal. The third set of wires are known as collection wires, they are not electrically connected; when drifting ionisation approaches the collection wires it is absorbed producing a uni–polar signal. In ProtoDUNE–SP each set of induction wires contains 800 wires at a 4.67 mm spacing, and each set of collection wires contains 480 wires at a 4.79 mm spacing.

The wire planes from each APA are read out by electronics mounted on the APA frame; these electronics are submerged in the liquid argon and therefore referred to as cold electronics (CE). A total of 2560 electronics channels are used to read out the data from each APA. The CE amplify, shape, and digitise the signals from the wires before transmitting them outside the TPC to the Warm Interface Boards (WIB). The WIBs collate the data from the CE boards along with timing information from the timing system and pass the data onto the Data Acquisition System (DAQ).

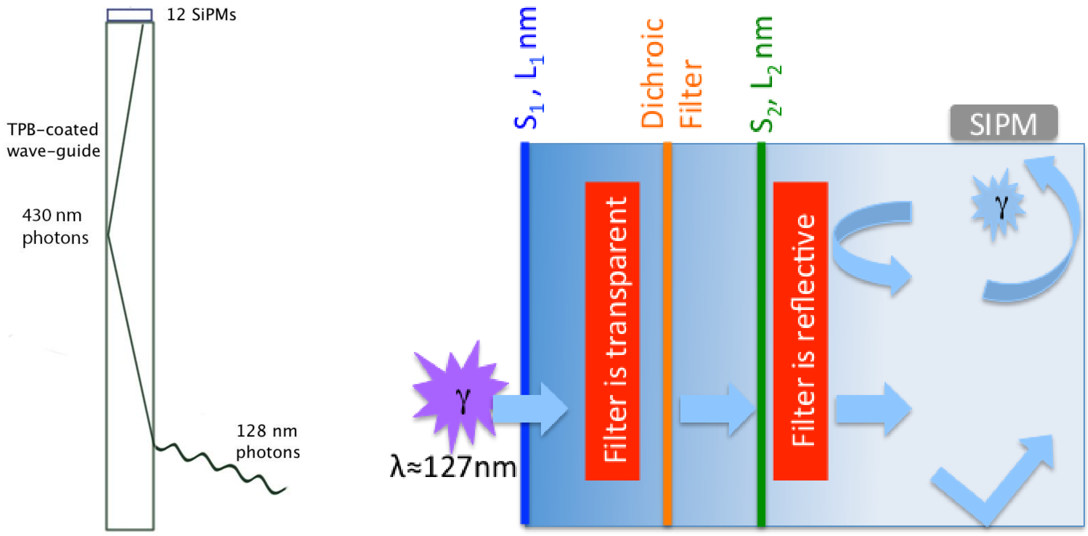
The cathode plane in ProtoDUNE–SP consists of an array of 18 CPA modules, 2 m (height) × 1.2 m (width). The cathode plane is held at -180 kV to provide a 500 V/cm drift field in each of the drift volumes. The field cage surrounding the drift regions ensures that the electric field is uniform across the detector volume by providing the necessary electrical boundary conditions.

One area in which the design of ProtoDUNE–SP differs from the far detector is the inclusion of the beam plug. This is necessary to minimize interactions between the charged particle test beam and the cryostat before the beam enters the active region of the detector. A cylindrical beam plug, containing nitrogen gas, penetrates from the cryostat wall into the field cage at location of the incoming test beam.

3.2.2 The Photon Detection System

The PDS in ProtoDUNE–SP is integrated into the APAs. Ten photon detector modules are embedded in each APA frame between the layers of wires on each APA face, as shown in Figure 3.3. Three types of photon detector module were tested in ProtoDUNE–SP, two very similar module designs based on coupling silicon photomultipliers to wavelength shifting bars, and a third novel design know as the ARAPUCA light trap. The operating principles of the two designs are illustrated in Figure 3.4.

The majority of the photon detector modules in ProtoDUNE–SP consist of wavelength shifting bars coupled to silicon photomultipliers (SiPM). Tetraphenyl-butadiene (TPB) is used to shift the wavelength of the light from ultra–violet to blue before the light is transmitted down the waveguide to the SiPMs. The main difference between the two nominal designs is in the wavelength of transmission within the waveguide; in one case the wavelength is transmitted at the blue wavelength produced



(a) Waveguide. **(b)** ARAPUCA.

Figure 3.4: The operating principal of the photon detector modules in ProtoDUNE–SP. Figure (a) from [53]. Figure (b) from [54]

by the TPB, in the other case the blue light from the TPB is first absorbed in the waveguide which then produces green light which is transmitted down the waveguide.

A small number of the photon detector modules in ProtoDUNE–SP feature a novel design known as an ARAPUCA light trap. In this design the photons are trapped in a small box through a sequence of wavelength shifting and optical filtering, significantly increasing the photon detection efficiency [55]. An ARAPUCA light trap consists of a 5 cm $\times$ 5 cm $\times$ 1 cm box which is coated with a highly reflective surface, on one side of the box is the filtering window, and on the other a SiPM. Incoming ultra–violet photons are shifted to the blue spectrum before passing through a dichroic filter which has a tunable wavelength cut–off at which it transitions from being transparent to reflective. After passing through the filter the photons are shifted again, this time from blue to green, such that if they get back to the filter it is reflective. As such green photons can be trapped within the ARAPUCA until they come into contact with the SiPM, providing increased photon detection efficiency. Each ARAPUCA photon detector module in ProtoDUNE–SP features an array of these traps arranged in a line across the width of an APA.

Unlike with the TPC electronics, there are no front–end electronics in the LAr volume for the PDS, the unamplified analogue signals are transmitted out of the

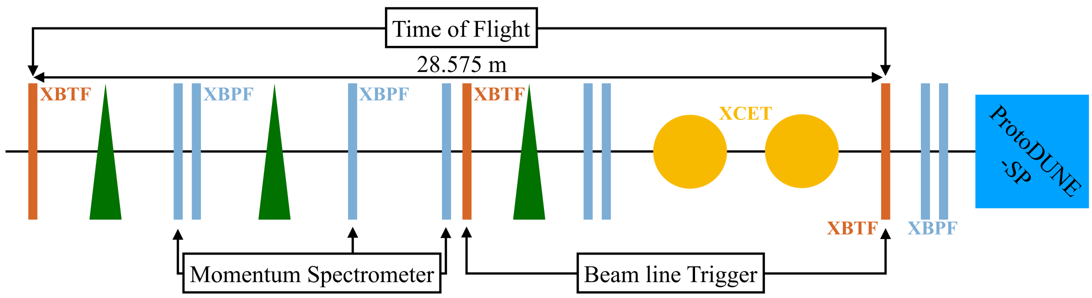


Figure 3.5: Schematic of the H4 beamline magnets and instrumentation. Figure from [56].

cryostat before processing and digitisation. Each photon detector module has 12 SiPMs which are read out in threes such that each module corresponds to 4 readout channels. The 40 readout channels from each APA are processes by four so called SiPM Signal Processors (SSP), which handle 10 channels each and are mounted on the top of the cryostat. After processing in the SSPs the PDS data is passed onto the DAQ along with the TPC data.

3.3 The H4 beamline

The ProtoDUNE–SP experiment is located at the end of the H4 beamline at CERN, the location of the beamline with respect to the detector is illustrated in Figure 3.7. The beam can be configured to provide hadron, muon, and electron beams with energies in the range 1–7 GeV into the detector.

The H4 beamline is a tertiary beamline which is produced when a secondary beam from the T2 primary target interacts with a secondary target. Particles from the secondary beam are selected based on momentum and charge before travelling down the H4 beamline to ProtoDUNE–SP. A schematic of the beamline instrumentation (BI) and magnets in the H4 beamline is given in Figure 3.5.

By combining momentum measurements from the profile monitors with time of flight (TOF) and Cerenkov measurements the beam momentum and composition can be measured. The predicted and measured distribution of TOF vs momentum for data from a number of runs at different momenta is shown in Figure 3.6. This

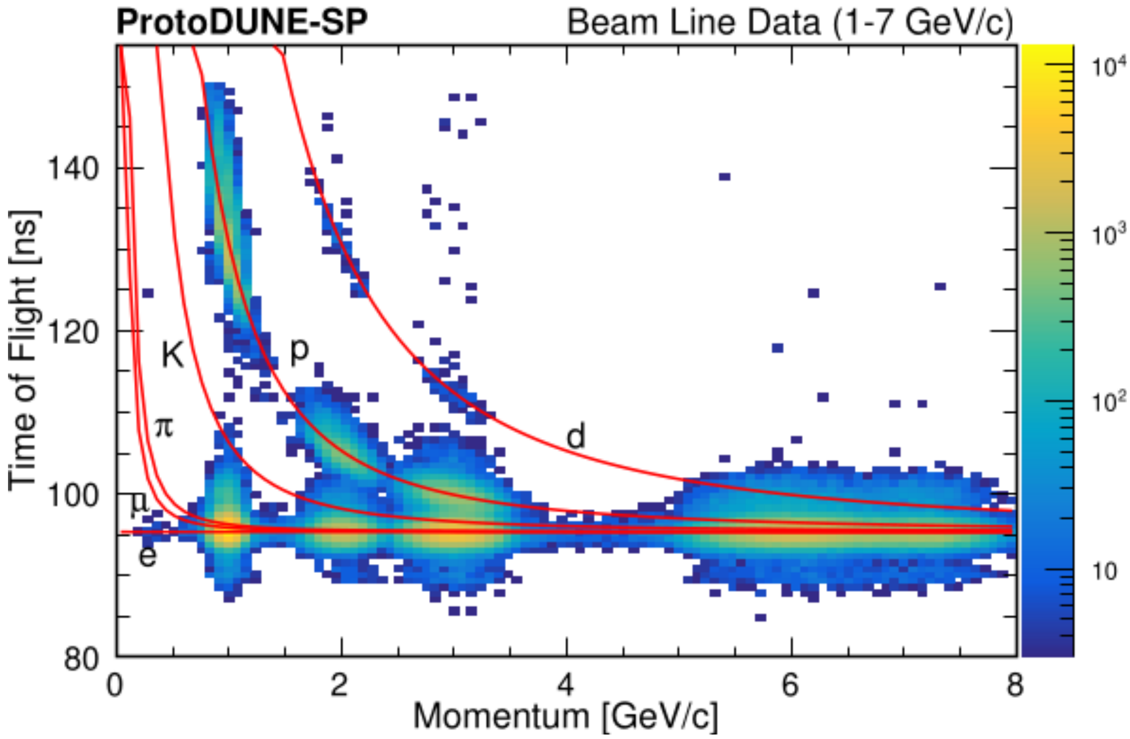


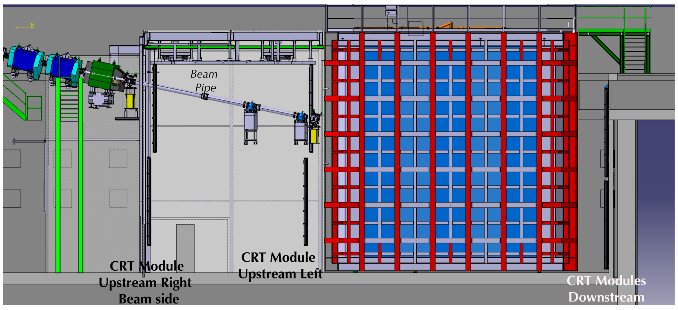
Figure 3.6: Time of flight vs momentum distributions from the H4 beamline instrumentation. Figure from [56]

information is used to trigger the detector during beam running, and is sent to the central trigger board for distribution to the detector components.

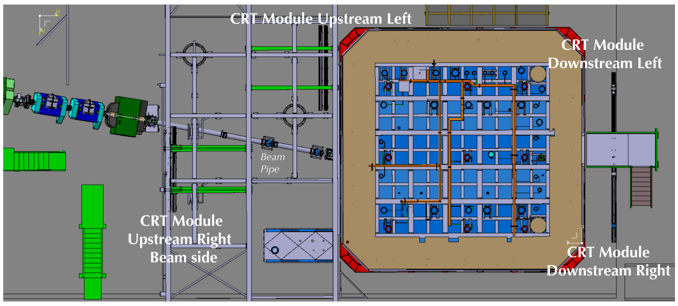
3.4 The Cosmic Ray Tagger

As a surface level detector with no overburden ProtoDUNE–SP measures a significant rate, on the order of 20 kHz, of cosmic ray muons, corresponding to an average of 60 muons per 3 ms readout window. These muons provide a useful source of calibration data in to form of long tracks and stopping muons. The Cosmic Ray Tagger (CRT) in ProtoDUNE–SP was installed on the upstream and downstream faces of the TPC to trigger the detector for cosmic–ray muons which travel parallel to the anode plane. In addition the CRT provides an additional source of t_0 tagged tracks for calibration.

The CRT consists of four parts, two upstream assemblies and two downstream assemblies, the locations of the CRT assemblies is illustrated in Figure 3.7. Each CRT assembly is constructed from overlapping scintillation counters which cover an area 6.8 m high and 3.65 m wide. Scintillation strips of length 365 cm and width 5 cm are



(a) Side view.



(b) Top view.

Figure 3.7: Location of the H4 beamline and cosmic ray taggers in relation to the ProtoDUNE–SP detector. Figures from [56].

placed in perpendicular arrays to give two–dimensional reconstruction within each CRT assembly. By combining data from upstream and downstream CRT assemblies with a time coincidence requirement the trajectories of tracks can be reconstructed.

3.5 The Data Acquisition System

Data from the TPC, PDS, and CRT in ProtoDUNE–SP are collated by the Data Acquisition system (DAQ). The DAQ distributes triggers, compresses and packages the data into events, monitors the data quality, and stores the data ready for future analysis. An overview of the ProtoDUNE–SP DAQ system is seen in Figure 3.8; there are four primary data flows in the system: TPC, PDS, CRT, and BI. Timing and triggering signals are distributed to the detector components by the timing board which maintains a 50 MHz clock and receives $\sim$ 40Hz of triggers from the Central Trigger Board (CTB) based on data from the BI and CRT [53].

The ProtoDUNE–SP TPC contains a total of 15,360 wires spread across the six APAs, the wires are digitized at a rate of 2 MHz resulting in an overall data

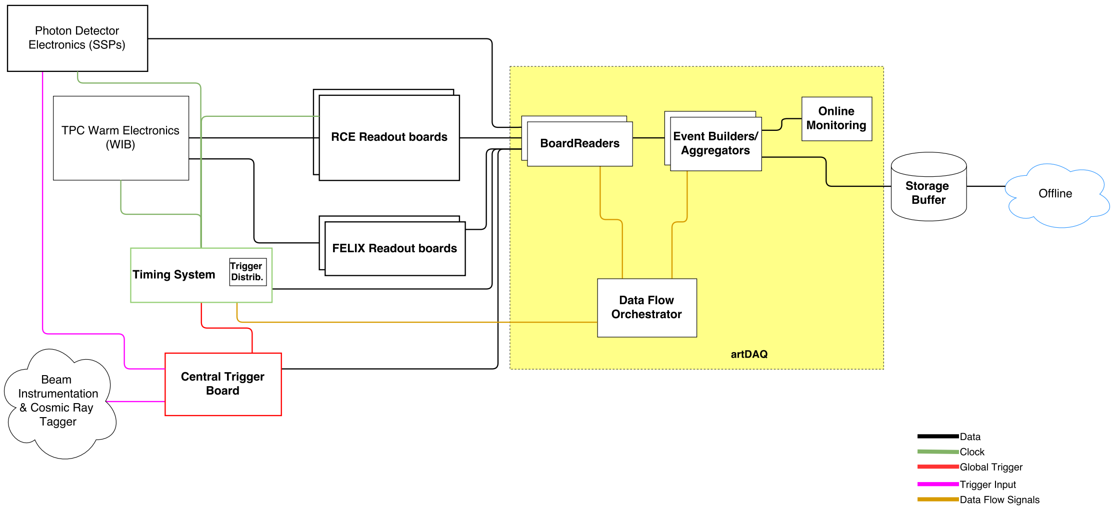


Figure 3.8: Outline of the data acquisition system in ProtoDUNE–SP. Figure from [53].

flow of around 480 Gb/s from the TPC electronics. An event in corresponds to a continuous readout of the detector for 3 ms, resulting in 6000 samples from each wire; data is buffered such that the readout window can be opened 250 μs before the trigger time. Data from the TPC is received by two systems, a system based on Reconfigurable Computing Elements (RCE) [57] handles the data from five APAs while data from the sixth is received by a system based on Front–End Link Exchange (FELIX) cards which have been developed by the ATLAS collaboration [58].

The software layer of the ProtoDUNE–SP DAQ is based on Fermilab's artdaq [59]. This component is primarily responsible for acquiring the data, packaging it, and storing it locally. Triggered events are queued and distributed to the board readers and event builders by the Data Flow Orchestrator. There are multiple board readers which are each responsible for processing the data from specific hardware components, details vary between specific board readers but generally these processes are responsible for formatting the data from each component ready for aggregation. Data from the various detector components are aggregated by the event builders, which are responsible for assembling the completed events. After compression events have an average size of 60 MB. Artdaq is also responsible for the real–time monitoring of data quality via the online monitoring system, this system will be discussed in Section 3.8.

3.6 Simulation

Simulation and reconstruction of ProtoDUNE–SP data takes place in the LArSoft framework [60]. LArSoft is a software suite for simulating and reconstructing data collected by LArTPC detectors based on the art event framework from Fermilab [61]. LArSoft is under active use and development by a number of participating LArTPC based experiments, with each experiment making use of its core functionality as well as experiment specific code. The simulation and reconstruction of ProtoDUNE–SP data in the LArSoft framework will be discussed in sections 3.6 and 3.7 respectively.

Simulation in LArSoft is broken down into three sequential stages: generation, propagation, and detector simulation. The initial state particles are produced in the generation step, the propagation and interaction of these particles in the detector is simulated during the propagation step, finally the transport of energy depositions and simulation of detector effects are handled by the detector simulation phase.

As a surface based detector in a test beam, ProtoDUNE–SP is subject to three main sources of particles: beam particles, beam halo particles, and cosmic ray particles. The beam particle and beam halo flux in the vicinity of ProtoDUNE–SP was provided by simulations of the H4 beamline [62] based on two simulation frameworks, G4beamline [63] and FLUKA [64]. The cosmic ray flux in ProtoDUNE–SP is simulated using CORSIKA [65]. Finally, low energy radiological backgrounds in LAr are simulated, these include ^{39}Ar,^{85}Kr, and ^{222}Rn.

After generation, the particles are allowed to propagate and interact in the detector geometry, including the cryostat, external systems, and experimental hall. This is simulated using GEANT4 [66] which tracks particles in small steps; the step size, $300\mu m$, is chosen to be much smaller then the spatial resolution of the detector to allow for small–scale processes like showering to be accurately simulated.

Particles which propagate through the detector during the propagation phase of the simulation leave energy deposits in the form of ionisation electrons and scintillation photons. It takes 23.6 eV to ionise a single argon atom and around 19.5 eV to produce a single scintillation photon, as such a minimum–ionising particle

(MIP), which deposits around 2MeV/cm in liquid argon, will produce tens of thousands of electrons and photons per cm.

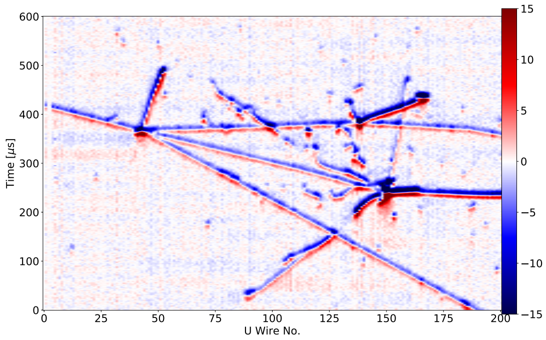
The detector simulation phase of the simulation chain is responsible for drifting the ionisation electrons towards the collection wires, propagating the simulated photons to the photon detectors, and simulating the response of the wires, SiPMs, and electronics to the signals. The shear number of ionisation electrons and scintillation photons produced in a ProtoDUNE–SP event makes simulating the propagation of the full set of particles impractical and therefore LArSoft employs approximation techniques to accurately predict the observed signals within a reasonable computation time. A number of detector effects are taken into account when simulating the electron drift: electron–ion recombination, transverse and longitudinal diffusion, electric field distortions due to space charge, and electron capture on impurities.

When the ionisation and scintillation signals arrive at the detector components, simulated waveforms are produced based on the induced signals produced in the detector components. These signals are converted into electrical signals by electronics simulation which is completed in LArSoft. The electronics simulation includes simulation of: electronics gain, noise, and analogue to digital conversion. The simulated waveforms produced by the ProtoDUNE–SP simulation are then compressed and stored ready for reconstruction.

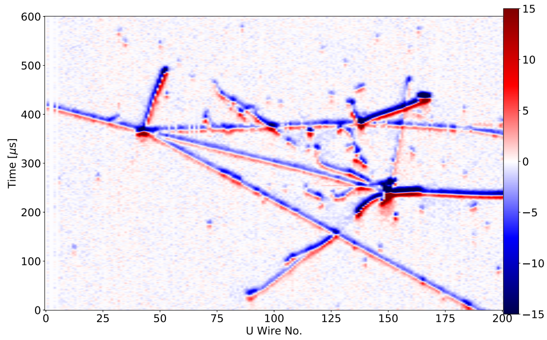
3.7 Reconstruction

An event consists of a synchronised set of waveforms from all of the TPC channels, with each event corresponding to 3 ms or 6000 samples. The particle interactions within each event are reconstructed into objects like tracks and showers which can be used for physics analyses, this sections provides a brief summary of the steps involved in this reconstruction.

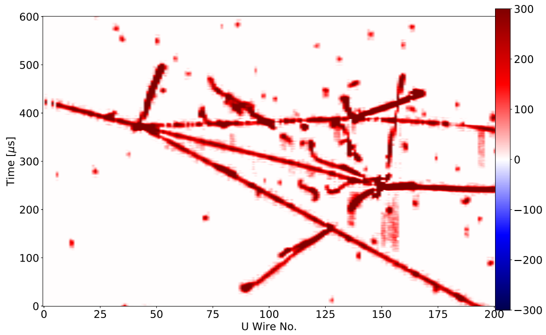
First, the TPC waveforms are passed through a set of filtering algorithms which are designed to reduce the noise on the waveforms, as well as to mitigate electronics effects such as sticky–codes and undershooting. An additional step known as a 2D



(a) Before noise filtering.



(b) After noise filtering.



(c) After 2D deconvolution.

Figure 3.9: Example of noise filtering and 2D deconvolution in ProtoDUNE–SP data. Figures from [56].

deconvolution is applied to extract the original signal from the measured signal given a detector response function for the wire in question as well as neighboring wires, this method has been described in detail by the MicroBooNE collaboration [67]. An example of the noise filtering and 2D deconvolution techniques applied to a 7 GeV test beam event in ProtoDUNE–SP data is given in Figure 3.9.

Once the deconvoluted waveforms have been calculated, regions of interest (ROI) are defined, these are regions of high amplitude in which charge deposition is likely to have occurred. Reconstructed hits are found within each region of interest by fitting gaussian peaks to the peaks within the region; most hits consist of a single gaussian peak, however in busy regions of the detector multiple gaussian peaks may be used to fit a single pulse. Each reconstructed hit will have an associated peak time, width, and integral, these objects form the basic input for the subsequent pattern recognition algorithms. An example of the reconstructed hits is shown in Figure 3.10.

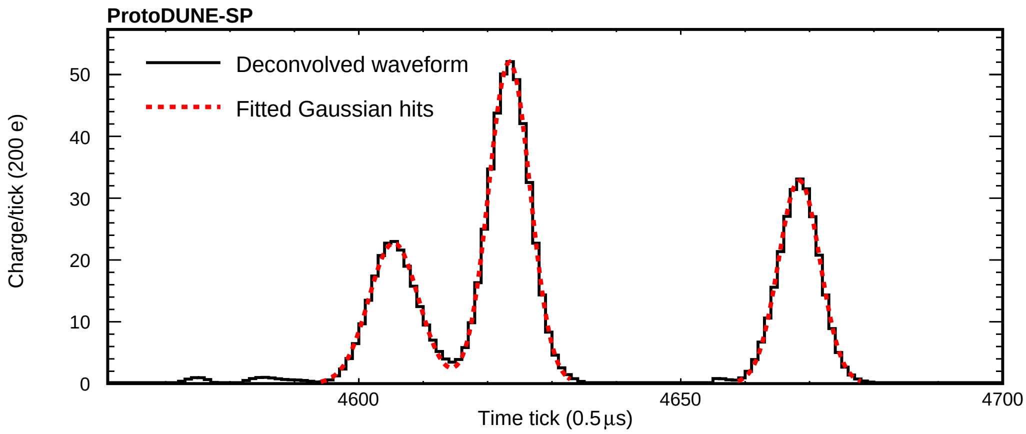


Figure 3.10: Reconstructed hits from ProtoDUNE–SP data. Figure from [56].

Pandora [68] is the primary pattern recognition software used in ProtoDUNE–SP. It takes a multi–algorithm approach to reconstructing particle interactions in the detector, and has been successfully used by other LArTPC detectors, such as MicroBooNE [69]. Pandora handles the clustering of hits into 2D clusters, the matching of 2D clusters into 3D clusters, as well as the reconstruction of 3D objects like tracks and showers. Ultimately Pandora returns a tree of reconstructed Particle Flow Particles (PFParticles), each corresponding to a distinct track or shower, and connected through parent–daughter relationships which define the particle flow in the interaction. Pandora reconstruction proceeds in two stages: a cosmic pass and a beam pass.

First the cosmic pass reconstructs the event with algorithms designed to reconstruct track–like particles. Track stitching algorithms can be used to assign a t_0 to tracks during this stage; any track which crosses either a CPA or APA will produce track segments on either side of the boundary, these segments point in the same direction but will have been displaced from each other in the drift direction based on the arrival time of the corresponding particle. The t_0 for that track is equal to half the time shift required to realign the two segments into a continuous track. After the cosmic pass any clear cosmic–ray candidates are removed under the following conditions [56]:

- The particle travels through both the top and bottom of the detector.

- The assigned t_0 is inconsistent with the beam time.
- If no t_0 assigned, try $t_0 = 0$. If any hits are reconstructed with positions outside of the detector this track is inconsistent with the beam time.

Beam particle reconstruction considers only the hits that were not removed by being labelled as clear cosmic–rays. These hits are formed into 3D slices which contain all the hits from a single parent particle and it's daughters. The slices are reconstructed under both the cosmic–ray and beam particle hypothesis, and a boosted decision tree (BDT) is used to determine whether a given slice is consistent with being a beam particle.

Under the beam particle hypothesis a more complex chain of algorithms is used to reconstruct a given slice, these algorithms are capable of reconstructing the particle hierarchies seen in the complex hadronic interactions from the ProtoDUNE–SP beam. These algorithms return the particle flow of the interactions in the form of PFParticles as well as the reconstructed interaction vertex for the primary beam particle. An example of the reconstructed particle hierarchy from a ProtoDUNE–SP beam event is shown in Figure 3.11.

As well as precise spatial reconstruction, LArTPCs provide excellent calorimetric information. To convert the measured charge of each hit into a reconstructed energy a number of spatial and dQ/dx dependent factors need to be taken into account. The reconstructed charge of each hit is given by the integrated area under the gaussian fit to that hit. The dx for each hit varies based on the direction of the track with respect to the wires, it is equal to the wire spacing divided by the sine of the angle between the wire and the 2D projection of the track onto the anode plane.

A number of factors affect the measured dQ/dx, these effects need to be corrected in order to recover the dQ/dx at the source of the ionisation. These factors are split into two parts in the ProtoDUNE–SP reconstruction:

- Corrections in the drift direction, X corrections. Examples include longitudinal diffusion, attenuation on impurities, and drift velocity variations.

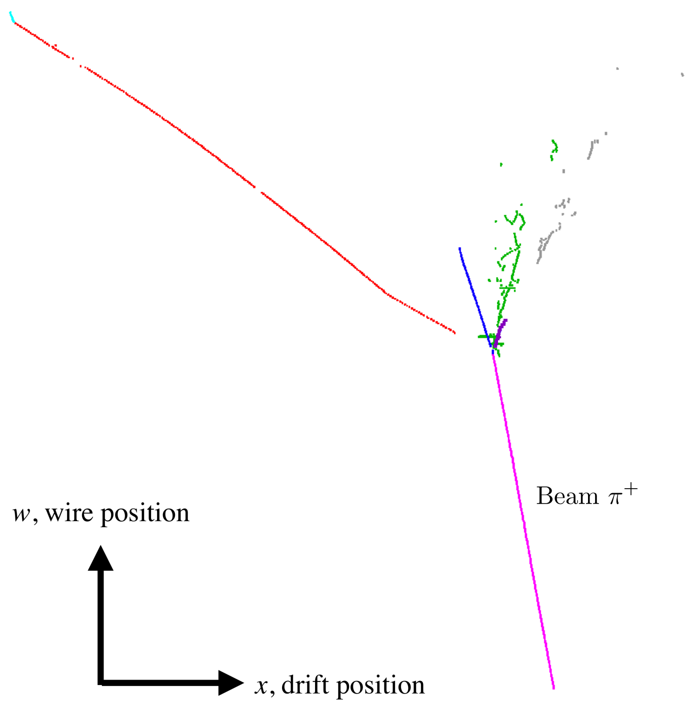


Figure 3.11: Reconstructed particle hierarchy from Pandora. Figure from [56].

- Corrections in the direction of the wire planes, YZ corrections. Examples include wire to wire response variations, transverse diffusion, and detector features such as electron diverters near the APA boundaries.

A calibration matrix is calculated for both sets of corrections by considering a sample of cathode crossing muons. The aim of these calibration matrices is to normalise the response over the TPC volume based on the median of the measured dQ/dx distribution in each location. The distribution is then normalised to the average value at the anode plane, where the effects of the X corrections are expected to be negligible. The corrected dQ/dx is given by

$$(dQ/dx)_{\text{corrected}} = N_Q C_{yz}(y,z) C_x(x)\,(dQ/dx)_{\text{reconstructed}}\,, \tag{3.1}$$

where N_Q normalises the median of the distributions to the median value at the anode, and C_{yz} and C_x are the calibration matrices for the YZ and X corrections respectively.

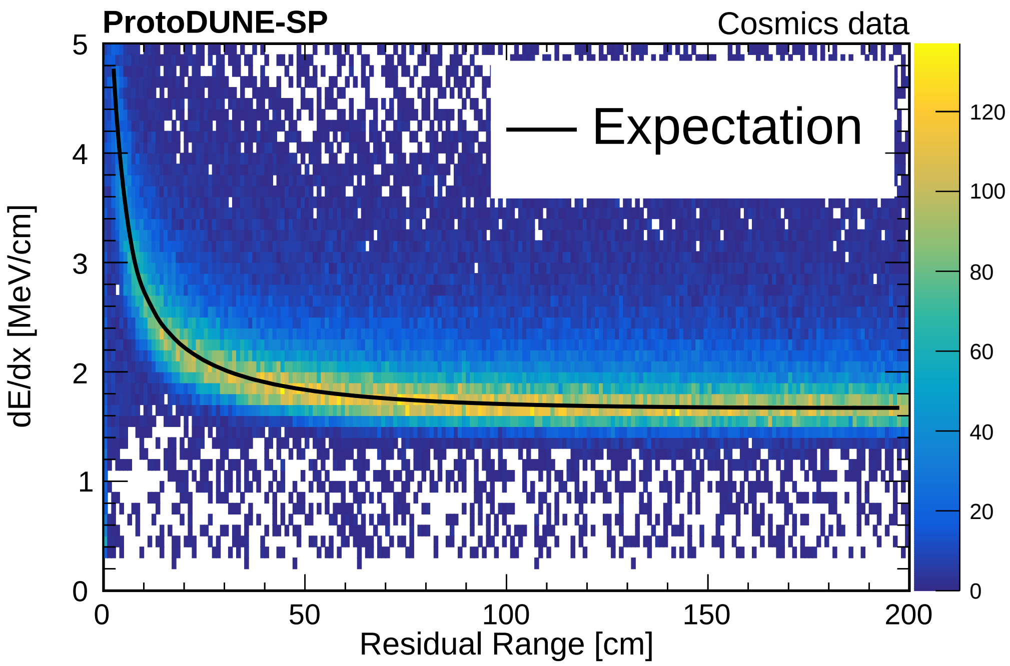


Figure 3.12: dE/dx vs residual range for a stopping muon sample in ProtoDUNE–SP data. Figure from [56].

The final step in energy reconstruction is to convert the corrected dQ/dx into a reconstructed dE/dx, this involves accounting for electron–ion recombination at the source. The modified box model is used to model the recombination correction, this model has been studied in a LArTPC by the ArgoNeuT experiment [70]. The reconstructed dE/dx is

$$\frac{dE}{dx} = \left(exp\left(\frac{\frac{dQ}{dx}}{C_{cal}} \frac{\beta' W_{ion}}{\rho\epsilon} \right) - \alpha \right) \left(\frac{\rho\epsilon}{\beta'} \right) \tag{3.2}$$

where C_{cal} is a calibration constant used to convert ADC to electrons, W_{ion} is the work function of argon, ϵ is the local electric field, ρ is the liquid argon density, and $\alpha = 0.93$ and $\beta\prime = 0.212$ (kV/cm)(g/cm^3)/MeV are the box model parameters as measured by ArgoNeuT. The calibration constant, C_{cal} is calculated by fitting the most probable value of the reconstructed dE/dx distribution as a function of range to the theoretical prediction for dE/dx vs range for a sample of stopping muons, as shown in figure 3.12.