Introduction to liquid argon time projection chamber operation and calibration methods

by

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Abstract

Neutrinos are an interesting type of particle that could provide insight to unanswered questions such as the imbalance of matter and antimatter in the universe. However, they're difficult, if not impossible, to detect directly. Modern particle physics experiments build detectors called Liquid Argon Time Projection Chambers (LArTPCs) that detect the products of neutrino interactions. Due to various processes that take place within the detector, the data that comes out of these detectors ends up being distorted; various calibration techniques are necessary to ensure that the data is accurate and undistorted. All of these aspects of LArTPCs are complex on their own, let alone when they are all occurring in tandem. In this paper I will describe the basic principles behind LArTPC operation and data collection, and the calibration techniques that are carried out in the detector. I will also provide a brief comparison of various data from several of the more recent LArTPC experiments. This description of basic principles may prove useful to people who are familiarizing themselves with LArTPC experiments as part of their research endeavors.

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I. Introduction

Neutrinos are a hot topic in high-energy physics right now, because there is so much we still don't know about them. We know they come in three flavors, but they can also oscillate between flavors; and while we can describe these oscillations mathematically, we don't know why it happens the way it does. We also don't know if there are more types of neutrinos out there that are even harder to detect. We know the flavors have distinct masses, but we don't know which mass corresponds to which flavor. This only scratches the surface of the mysteries of the neutrino. The hope is that by learning more about neutrinos, we can answer these questions and hopefully even answer questions about the wider universe, like why our universe is dominated by matter, and where the theoretically corresponding antimatter went.

Nothing in this world is ever easy, though - neutrinos are very difficult to actually detect. They don't have a charge, so they can't be detected electrically; they only interact via the weak nuclear force and gravity [1]. And they are so incredibly small that they rarely interact with anything even via those channels: "a lightyear of lead would stop only about half of the neutrinos coming from the sun" [2]. And there are quite a large number of neutrinos coming from the sun - 2×10^{38} - or 200 billion billion billion billion - every second! [1] That's not even taking into account neutrinos coming from other parts of the universe, like supernovae, cosmic rays, etc.

If neutrinos are so difficult to detect, then how can we learn more about them? Well, they do still interact with things, it's just quite infrequent. To increase the likelihood of getting as many interactions as possible, we make our neutrino detectors very large; and when we generate beams of neutrinos, we make them very concentrated.

II. LArTPC Operation

Liquid argon time projection chambers (LArTPCs) are one type of detector that has been created for the detection of neutrinos. They are large chambers called cryostats, filled with liquid argon (LAr), held at cryogenic temperatures. For example, DUNE is going to be comprised of four such detectors, containing a grand total of 70,000 tons of liquid argon [3], where 40,000 tons of the liquid argon will form the active part of the detector, and the rest will surround it to create a margin between the field cage (the outside of the detector) and the outer walls of the chamber. Neutrinos enter the detector and undergo various types of interactions with argon. The particles which are produced by these interactions then travel through the length of the detector, ionizing the liquid argon its path and creating a streak of argon ions (Ar+) and freed electrons.

The TPC has, along its length, a cathode plane and an anode plane of wires forming a grid. The planes are kept at a very high voltage difference, creating an electric field within the chamber. The electric field causes electrons and Ar+ atoms to drift toward the anode or cathode, respectively, drifting perpendicularly to the length of the detector. As drifting electrons pass by the wires, they will induce a current in the wires they are close to. Later, these induced currents can be traced backwards to the point where their respective wires intersect, thus identifying the exact point in the detector that the drifting electron was located at the time it crossed the wires.

Time information is obtained in a few ways: one way is to get the start time t_0, when the neutrino first started reacting with argon, from photodetectors in the TPC that detect photons produced by the argon when it becomes excited. Another way is from knowing the timing of the beam, i.e., when the neutrino source “turns on”, and knowing how long it will take to arrive at the detector.

Once you know how long the electron has been drifting, you can combine all this information to find where in the detector these electrons originated from; and thus you will be able to see the path that the original particle took when it generated the electrons. This is the data we actually want, because once we see the paths that particles took through the detector, we can identify which tracks are the result of neutrino interactions as opposed to other particles. We can deduce information about those interactions by how much energy they imparted to the detector, which is in turn determined by how much of the argon was ionized.

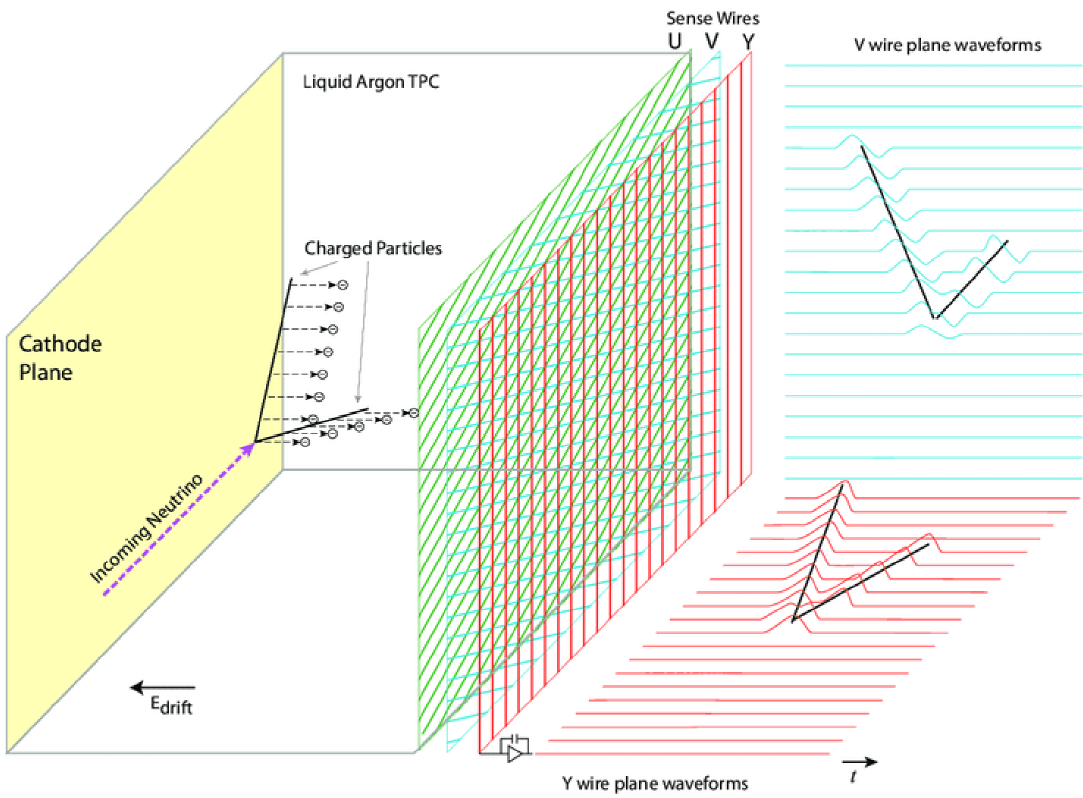

Figure 1: LArTPC schematic [4].

III. Particle identification

In order to identify the types of particles which travel through the detector, we need to know how they behaved. While we can't measure this directly, we can measure other things resulting from these behaviors and work backwards. As discussed in section II, the thing the detector actually detects is electrons; of particular interest are the electrons which were separated from their parent argon atoms by some ionizing particle passing through (the ionizing particle being the result of neutrino interactions). The type of ionizing particle (electrons, muons, etc.), as well as how much energy it has, will determine how much of the argon in its path it will be capable of ionizing, as well as how far through the detector it is likely to travel. The particle species will also determine what the very end of the path will look like, when the particle dumps what's left of its kinetic energy. Thus, the appearance of the path and how many particles are ionized along it will allow us to determine which type of particle caused it. We already know what types of neutrino interactions are possible which can result in these ionizing particles; so we will also be able to learn about the relative frequency with which these interactions occur in relation to one another. An example of a possible neutrino interaction is shown in figure 2.

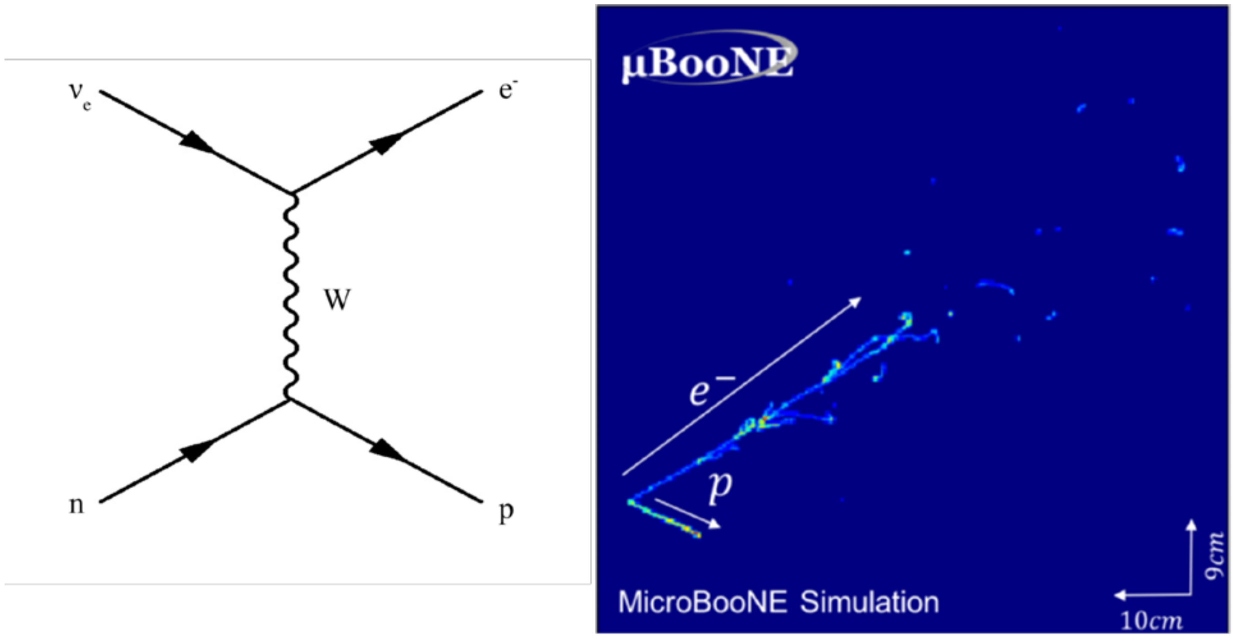

Figure 2: a) A Feynman diagram depicting an electron neutrino interaction with a neutron in an argon nucleus. b) Event display from MicroBooNE of the results of this interaction, a proton (the shorter, more intense track) and an electron (the longer track with several showers) [5].

The electrons which are liberated by the ionizing particle will drift toward the anode, due to the electric field in the detector. They are detected via the current they induce in the wire plane. Since the charge of an electron is known, this electrical current data can immediately tell you how many electrons there are, as well as where in the detector they originated (based on where the wires of the wire plane cross at the point where the electron reached the plane). This lets you reconstruct the path travelled by the ionizing particle. When combined with the number of charges, this gives dQ/dx - the number of ionized charges per unit length along the trajectory of the ionizing particle.

We can relate dQ/dx to the energy deposited per unit length, dE/dx, as seen in section V. Rather than looking at how many argon atoms were ionized along the path, we look at how much energy was transferred from the ionizing particle to the LAr along its path. Most particles will have pretty similar dE/dx values initially, because they are all minimum ionizing particles so they deposit the minimum amount of energy possible along their tracks. If they have similar values, then how does this help us distinguish different types of particles? It turns out that when dE/dx is plotted vs residual range (distance from the end of the path), there will be different distributions for different types of particles. The particles will have different behavior at the ends of their tracks. For example, protons tend to have short tracks with high dE/dx, whereas electrons have longer tracks with more particle showers, as shown in figure 2 [5]. Once we identify which types of particles left tracks in the detector, we can begin to estimate how many of them came from neutrino interactions, and how frequent the various types of neutrino interactions are. The more we can learn about neutrino interactions with matter, the closer we will be to solving some of the mysteries of the neutrino.

IV. LArTPC calibration

There are lots of effects which occur in the detector that distort the data, which can be minimized but not entirely prevented. These effects must be known as precisely as possible so that the raw data can be corrected, in order to accurately represent the energy which was imparted to the detector by the original high-energy particle.

i. Electronics response

Nothing in this world is perfect, and that includes electronics: there are always deficiencies or imperfections that cause them to function below what is predicted by theory. To see the actual response of the electronics rather than just count on the theoretical response, detectors are constructed with a built-in ability to inject a specific amount of charge directly into the electronics input to compare the charge detected to the charge that was input. More details can be found in ref. [6].

ii. Electric field within the detector

The electric field is determined by the voltage difference between the wire planes. The electric field can be verified by looking at freed electrons velocities as they travel along the electric field lines. Their velocity in an E-field of a given strength is known [7], so by comparing what it is expected to be and what they actually detect, they can map out the electric field discrepancies throughout the detector volume. More details can be found in ref. [6].

iii. Space charge effects

One source of electric field distortion is via space charge effects. When argon is ionized, the electrons and argon ions move toward the anode and cathode respectively; but because the argon ions are so large, they move quite slowly and can exist in the detector for several minutes before they are neutralized at the cathode. As a result, the cloud of Ar+ in the detector affects the electric field: near the cathode it will increase the electric field, and near the anode it will decrease the electric field. This, in turn, affects the electrons' energies and trajectories. To correct for this effect, there are several methods. The first is to use a laser track; when you direct it through the LAr, it will ionize argon, and you can measure the drifting electrons. Their arrival time will be affected by the distorted electric field, so by comparing the measured drift time to the predicted drift time, you can identify distortions in the detector's electric field. Another method is to use nearly-intersecting muon tracks, as described in ref [6].

iv. Electron attachment to impurities

The liquid argon in the detector is highly pure; but there are small amounts of impurities remaining in the liquid volume, primarily water, oxygen, and nitrogen. These molecules can attract electrons and bind to them, reducing the number of electrons which reach the wire-plane and making it seem like less energy was imparted to the detector than there actually was. All LArTPCs have purification systems and purity monitors built in. Additionally, the attachment rate for each type of impurity has been measured, so we know the amount by which the detected electrons have been reduced. More details can be found in ref. [6].

v. Diffusion of the electron cloud

When the ionization electron cloud drifts through the detector, they spread out (diffuse) through the liquid, and the electron cloud "smears". The diffusion is not isotropic; rather it is oval-shaped: the electrons don't "smear" as much in their drift direction (longitudinal) as they do in the plane perpendicular to it (transverse). The electrons are then detected over a larger number of wires than they would have if the cloud had not spread/smeared, resulting in a spread out, blurry "image". However, this doesn't affect the charge reconstruction, so long as you integrate the total charge under the pulse (the burst of current resulting from the cloud of detected electrons), which is the usual practice. More details can be found in ref. [6].

vi. Electron recombination with argon ions

When argon in the detector becomes ionized, the freed electrons drift through the detector. As they drift and bump into other argon atoms and experience the force from the E field, they lose energy, until they come into equilibrium with the surroundings, meaning they're moving at the drift speed determined by the electric field [6]. This can give them more opportunity to recombine with nearby Ar+, if their drift velocity is slow enough, since moving slower gives them more time near the surrounding Ar+, and thus more opportunities for the Ar+ to capture the electrons and form neutral Ar once more. Conversely, if the drift velocity is higher, the electrons will spend less time nearby Ar+ and thus there will be a lower rate of electron-ion recombination.

The drift velocity is determined by the electric field within the TPC, which is primarily determined by the voltage difference between the cathode and anode, as discussed in section II. However, the electric field can be distorted, as mentioned in section IV.iii, by space charge effects - a large enough cloud of ions, while it exists within the body of the detector, will increase the electric field, which will increase the drift velocity of the electrons and reduce the expected recombination rate. This is one example of the effect these distortions have not only on the data itself, but on each other, despite being distinct processes.

There are two mathematical models that are used to calculate the expected rate of recombination [8]; these will be discussed further in section V of this report. Furthermore, the likelihood of an electron recombining with an argon ion decays exponentially the further the electron travels from the cloud of argon ions - of course, when it is surrounded by ions, the electron is much more likely to become attached to one of them than when it moves beyond and is instead surrounded by un-ionized argon.

V. Examples of data from existing experiments

In this section, I will explain what typical data looks like, and provide examples from existing experiments.

In order to identify the types of particle interactions which took place in the detector, we need to obtain dE/dx. However, the data that you get from running the detector is actually dQ/dx. dQ/dx and dE/dx are related to one another via the modified box model [8,9],

$$\left(\frac{dE}{dx}\right)_{calibrated} = \left(\left(\left(\frac{dQ}{dx}\right)_{calibrated} \frac{\beta\prime\, W_{ion}}{\rho\, E}\right) - \alpha\right)\left(\frac{\rho\, E}{\beta\prime}\right) \qquad \textbf{(1)}$$

where W_{ion} is the average ionization energy of argon; ρ is the density of liquid argon; E is the electric field in the detector; and α and β' are empirical parameters which are found through measurement (they are largely based on the material properties and the electric field inside the detector). dQ/dx is the number of electrons detected at the collection plane per unit length. It is found via another equation [9]:

$$\left(\frac{dQ}{dx}\right)_{calibrated} = \frac{\left(\frac{dQ}{dx}\right)_{raw}}{C_{cal}} C_x(x) C_{yz}(y,z) C_t(t) \qquad \textbf{(2)}$$

where $(dQ/dx)_{raw}$ is the raw detector data, in units of "ADC ticks (detector counts) per unit length; $C_x(x)$ is a calibration variable which accounts for diffusion and electron attachment to impurities; $C_{yz}(y,z)$ accounts for space charge effects and electronics; $C_t(t)$ accounts for variations in the argon purity and electronics over time; and C_{cal} is responsible for converting the units of dQ/dx from ADC ticks per unit length to electrons per unit length.

The modified box model is, as the name implies, a modification of something called the box model, which was based on Jaffe's columnar theory describing recombination of electrons within the column of ionized argon. The box model simplified this theory by making the approximation that electron and ion diffusion in liquid argon has a negligible effect on recombination. There is also Birks' model, which made a different simplification which was originally developed to model the light yield from scintillators, which are materials which generate light in response to ionizing radiation. The box model and Birks' model were accurate over different ranges of ionization density; the modified box model introduced modifications which made it work better for the electrons drifting through liquid argon, which are produced by ionizing particles with a wide range of dE/dx. There are several parameters in this model which vary from detector to detector. Once these parameters are known, you can then convert any dQ/dx to the corresponding dE/dx and proceed with particle identification, as described in section III.

To find the calibration parameters, you can use data which you are certain came from muons (for example, MicroBooNE used cosmic ray muons) and compare it to the theoretical predictions, which for muons are very well understood. By graphing dQ/dx from these muons versus the theoretical dE/dx, the calibration parameters can be determined by making small adjustments until a curve fit of the modified box model aligns with the graph. Figure 3 shows plots of dQ/dx versus dE/dx from MicroBooNE [9]. Table 1 shows the resulting calibration parameters for ArgoNeuT [8], MicroBooNE [9], and ProtoDUNE [10].

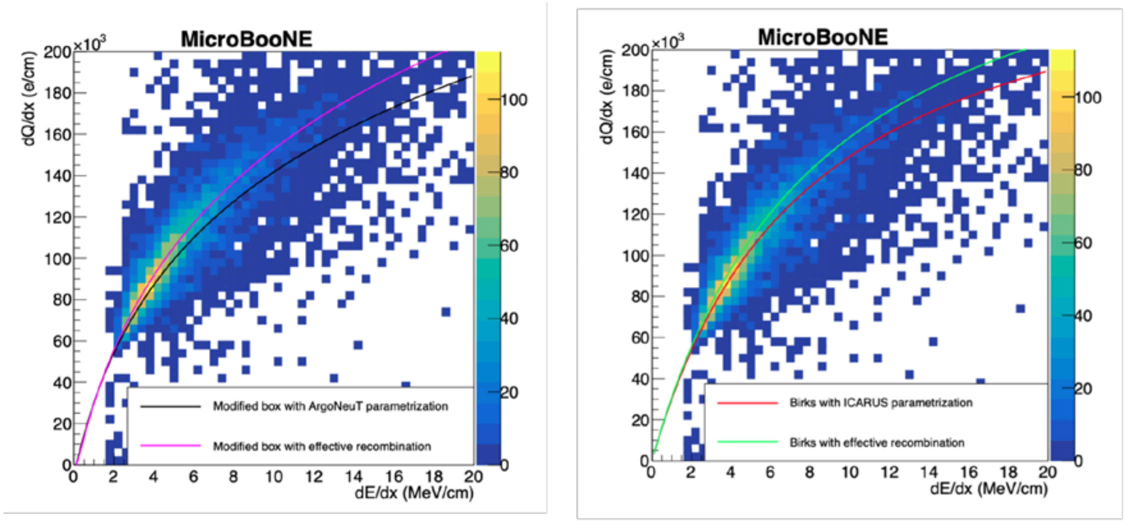

Figure 3: dQ/dx vs dE/dx from MicroBooNE. (left) This figure uses the modified box model. The black line uses parameters already found from ArgoNeuT; the pink line uses parameters from MicroBooNE's own calibration. (right) This figure uses Birks' model. The red line uses parameters from ArgoNeuT; the green line uses parameters from MicroBooNE. These figures are reproduced from ref. [9] with permission.

	Fitted value of C_{cal} (from simulation) (ADC/e)	**Fitted value of C_{cal} (from data) (ADC/e)**	**α**	**β' ((kV/cm)(g/cm^2)/ MeV)**	**E (V/cm)**
ArgoNeuT	-	-	0.93 ± 0.02	0.212 ± 0.002	481
MicroBooNE	$(5.077 \pm 0.001) \times 10^{-3}$	$(4.113 \pm 0.011) \times 10^{-3}$	0.92 ± 0.02	0.184 ± 0.002	273
ProtoDUNE	$(5.03 \pm 0.01) \times 10^{-3}$	$(5.4 \pm 0.1) \times 10^{-3}$	-	-	-

Table 1: Comparison of calibration constants for ArgoNeuT [8], MicroBooNE [9], and ProtoDUNE [10].

Once you have dE/dx for your data, you can graph it versus the residual range. The resulting graphs will be shifted for different types of particles, thereby identifying and distinguishing them from one another. Figure 4 shows a graph of dE/dx versus residual range from ProtoDUNE. Note particularly the distinct curves belonging to muons versus protons.

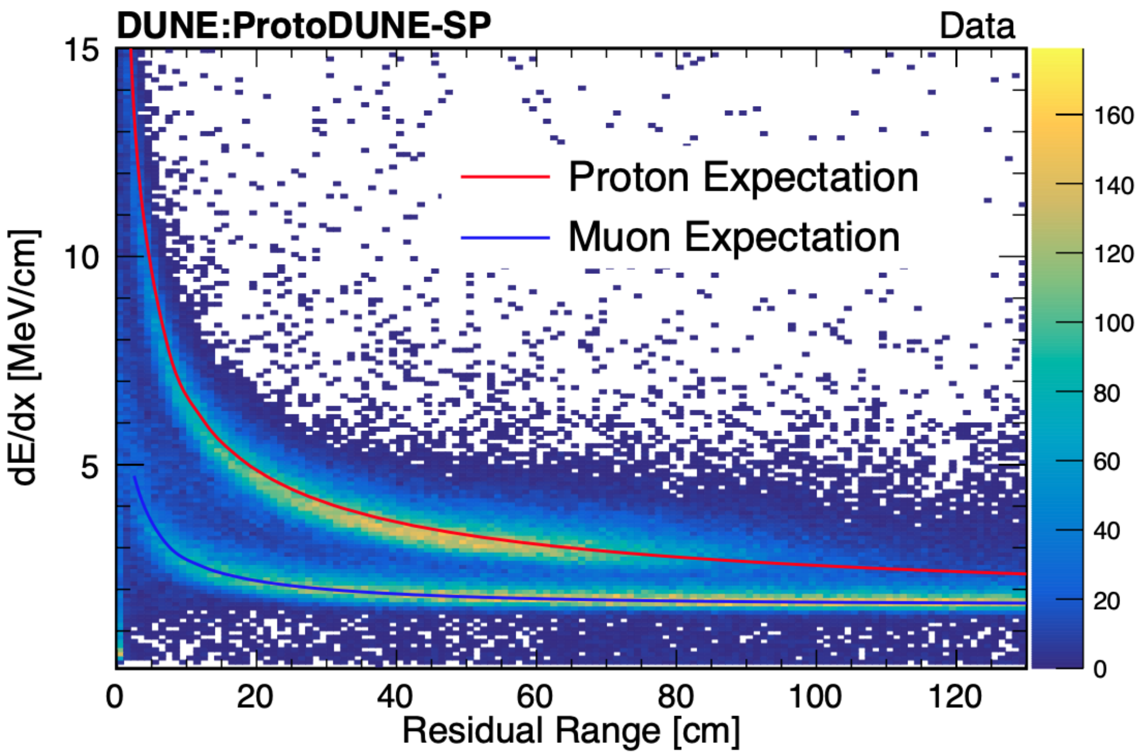

Figure 4: dE/dx vs residual range from ProtoDUNE [10].

VI. Conclusion

In this report, I provide a simplified explanation of how LArTPCs function, how they are calibrated, and why they are useful for learning about neutrinos. I also explain what kind of data is obtained from LArTPCs and give several examples of data from existing LArTPC experiments. This simpler introduction to the big picture of LArTPCs may be a useful entryway into more complicated literature about the finer details of these detectors.

References

[1] M. Thomson, Modern Particle Physics (Cambridge University Press, 2013).

[2] Glashow Event FAQ, https://icecube.wisc.edu/news/glashow-event-faq/.

[3] B. Abi et al., J. Inst. 15, T08008 (2020).

[4] V. Radeka et al., J. Phys.: Conf. Ser. 308, 012021 (2011).

[5] P. Abratenko et al., Phys. Rev. D 103, 092003 (2021).

[6] T. Yang, Instruments 5, 2 (2021).

[7] W. Walkowiak, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 449, 288 (2000).

[8] R. Acciarri et al., J. Inst. 8, P08005 (2013).

[9] C. Adams et al., J. Inst. 15, P03022 (2020).

[10] B. Abi et al., J. Inst. 15, P12004 (2020).