On Beam Matching and the Space-Charge Effect in protoDUNE-SP

Jesal Mandalia

06/09/2017

Supervisors: Dr. L. Whitehead and Dr. S. Bordoni
Abstract

In this project simulations using LArSoft have been analysed in particular looking at how the space-charge effect will affect the matching of particle tracks from the beam line monitor to the TPC and the TPC’s performance measuring $\frac{dE}{dx}$ in protoDUNE-SP. The analysis here provides some preliminary calibrations for protoDUNE-SP to account for the impact the space charge effect will have. Many areas of pion cross section analysis will be affected by the space charge effect so it is vital for a calibration to be developed.
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1 Introduction

DUNE (Deep Underground Neutrino Experiment) is a planned next-generation long-baseline neutrino oscillation experiment. The DUNE collaboration will use a Liquid Argon Time-Projection Chamber (LArTPC) for the detection of particles. At CERN there are currently two prototypes for DUNE under construction protoDUNE-DP (Dual Phase), and the focus of this project, protoDUNE-SP (Single Phase) [1]. The protoDUNE-SP detector is an engineering prototype using full scale components and will collect test-beam data at the H4 beam-line in 2018. The collection of test beam data will be useful for knowing the particle entering the detector, the particle’s energy calibration and for a full characterisation of the detector response to be achieved. Measurements taken from protoDUNE-SP will be used to finalise the design for DUNE. Collected data will also allow for a measurement of the pion interaction cross-section in liquid argon helping to understand the neutrino interactions that will be seen in DUNE.

In this project simulations using LArSoft have been analysed in particular looking at how the space-charge effect will affect the matching of particle tracks from the beam line monitor to the TPC depicted in Figure 1.1.

![Figure 1.1: Figure showing the track in the TPC being matched up with the beam monitors.](image-url)
The programs used in this project for the analysis are:

- LArSoft v06.39 [2]
- ROOT 6.08/06 [3]

The results in this report come from MCC9, +3 GeV files.

1.1 Time Projection Chamber

The far detectors for DUNE will be liquid argon time projection chambers depicted in Figure 1.2. Charged particles traversing the volume of the TPC will ionise the argon atoms along its trajectory which will emit light. Between the end plates a high electric field is applied so that the released electrons drift towards the anode. At the anode the electrons are detected and a two dimensional projection can be read out with the arrival time of the charge giving the third dimension. This produces three dimensional images of the event.

Figure 1.2: Schematic of TPC with wire readout [4].
1.2 The Space-Charge Effect

The space-charge effect occurs as a result of a build up of slow moving ions in a region of the TPC which distorts the electric field. This distortion leads to a reconstruction problem that needs to be understood and considered in order to characterise the detector. As protoDUNE-SP will be on the surface this will be mostly due to ionisation from cosmic rays [5]. The following Figure 1.3 gives a diagrammatic representation of the space-charge effect:

![Figure 1.3: Diagrammatic representation of space-charge effect](image)

1. The reconstructed track shortens laterally and looks rotated
2. The reconstructed track bows towards the cathode

For the following analysis two sets of simulated files were used; one with and without the space charge effect. This analysis focuses on studying the effect of this distortion by comparing the two simulations.
1.3 The Energy Loss per Track Length for Particle Identification

The energy loss per track length or $\frac{dE}{dx}$ can be used to identify particles. The energy loss of a charged particle by ionisation has a dependence on the velocity of the particle. Different particles will have different $\frac{dE}{dx}$ shown in Figure 1.4. Therefore, being able to correctly identify $\frac{dE}{dx}$ is essential when specific particles need to be looked at.

Particle ID by $dE/dx$

Figure 1.4: $\frac{dE}{dx}$ for different particles [6].
2 Track Reconstruction and the Effect of the SCE

2.1 Tracks from Beam

To ensure that the analysis of the tracks from protoDUNE are pertinent to the beam a selection criterion must be used. The first selection criterion used in the analysis is to only include track start points around 1 m$^3$ of the expected beam position. This thereby excludes many tracks from a different origin, such as cosmic rays. ProtoDUNE will be on the surface and will have many cosmic ray tracks to account. Therefore the selection criteria is used to focus on tracks that start close to the beam window (where beam particles enter the detector).

2.2 Purity and Completeness

The following figures showing track purity Figure 2.1 & 2.2 and completeness Figure 2.3 & 2.4. These indicate the quality of the tracks being reconstructed. Purity here is defined as the fraction of hits that come from the matched particle divided by the total number of reconstructed hits [1]. Completeness is defined as the fraction of the number of true hits that are found in a track divided by total number of true hits in the object [1]. These can be used to form a selection criteria in order to analyse the tracks which have the best reconstruction.
Figure 2.1: Track purity without SCE.

Figure 2.2: Track purity with SCE.

Figure 2.3: Track completeness without SCE.

Figure 2.4: Track completeness with SCE.
2.3 Track Vertex

To understand the difference the inclusion of the SCE has on the simulation a comparison looking at the start points of each track for the true Monte-Carlo simulation and the reconstructed start point is shown in Figure 2.5. The $x$ and $y$ direction only have minor shifts; the $x$ towards the left and the $y$ towards the right. The effect is greatest in the $z$ direction with an approximately 20 cm shift. Therefore, this shift, which is considerably large, will need to be accounted for when reconstructing data that will be take by protoDUNE-SP. The work completed here can be used to form the basis of a simple calibration for protoDUNE before the full space-charge calibration is implemented.

![Figure 2.5: Comparison of True - Reconstructed Start Points in the $x$, $y$, and $z$ direction with and without the space-charge effect.](image-url)
2.4 Extrapolating to Beam Start Point

To find the origin of this 20 cm shift further investigation into the difference in the $x$, $y$, and $z$ components of the reconstructed vertex back to the true Monte-Carlo production point is needed. Only tracks from the beam and tracks that start in the active volume of the TPC were chosen. Using basic geometry these tracks were extrapolated back to the beam start point, which is approximately 2 m upstream. The difference being looked at is shown by the difference in two lines in Figure 2.6 at the beam start point. The position of the beam start point is $z = -196$ cm so the difference between the reconstructed track and the true start point gives indication on how well matched to the beam tracks in protoDUNE will be.

As seen in Figure 2.7 the inclusion of the space-charge effect results in noticeable shifts of approximately 10 cm in the $x$ direction and 15 cm in the $y$ direction. These shifts are large in comparison to the beam window, which is 250 mm in diameter, and so must be corrected for. This analysis can form the basis of a correction before the full space-charge calibration can be implemented.
Figure 2.7: The difference between the true and reconstructed points in the $x$, $y$ and $z$ direction. The blue line shown uses a simulation not accounting for the space-charge effect and the red line displays a simulation including the space-charge effect.
2.5 The Origin of the Shift

To determine where the shift in $x$ and $y$ originates from, as demonstrated in the previous Figure 2.7, the reconstructed vertex position used was replaced by the true vertex position shown in Figure 2.8. Using the true vertex shows the effect of the direction on the extrapolation. The difference in the $x$ direction is approximately 6 cm and the difference in the $y$ direction is approximately 11 cm.

![Figure 2.8: Difference in the $x$, $y$, and $z$ using the reconstructed direction and true start position with the space-charge effect.](image)
The following Figure 2.9 has used the true direction and reconstructed vertex position to replace those used in the previous section. The difference in the $x$ direction is approximately 4 cm and the difference in the $y$ direction is approximately 4 cm.

![Figure 2.9: Difference in the $x$, $y$, and $z$ using the true direction and reconstructed start position with the space-charge effect.](image)

The differences in the $x$ and $y$ directions from Figure 2.8 and Figure 2.9 are additive and are compatible with the mean figure seen in Figure 2.7. Therefore, it can be concluded that the largest contribution to the shift due to the space-charge effect is as a result of the reconstructed direction.
This information can be used to form a preliminary calibration for protoDUNE whilst waiting for a full calibration. Taking the histograms for the reconstructed direction and the reconstructed vertex position in Figure 2.7 and using a Gaussian distribution for each direction the histograms can be fitted. The following Figure 2.10 indicates the difference in the mean $x$ value is 11 cm and the difference in the mean $y$ value is 17 cm. Using the mean values for each of the Gaussian distributions the peaks of the histograms have been shifted to zero shown in Figure 2.11. These values give us a preliminary calibration for protoDUNE, which can be used before the full SCE calibration is complete.

Figure 2.10: The reconstructed direction and reconstructed vertex point fitted with a Gaussian distribution.
Figure 2.11: Using the difference in mean, found in the Gaussian fit, the peak of these distributions has been moved to 0.
3 Space-Charge Effect on Energy Loss as a Function of Track Length

3.1 Track Quality

When reconstructing the track length accuracy is vital since the energy loss per track length is used for particle identification. Therefore, any affects that the space-charge effect will have in the measurement of track length will be problematic when trying to identify certain particles.

Track length here is distance between start and end point of track. The residual range is the distance left between a given hit and the end point of a track shown in Figure 3.1. Using this along with the energy loss per track length for the three planes in protoDUNE seen in Figure 1.2 the following Figure 3.2 has been plotted. The gradient of the curve in the region below 20 cm increases more in this region due to other particle interactions occurring at the end of the track.

![Figure 3.1: Figure showing $T = Length_{trk} - Res_{range}$.](image)

Therefore, applying a 20 cm selection criterion on the residual range will ensure that $\frac{dE}{dx}$ vs residual range should leave a line with approximately zero gradient.
The track length and residual range along with $T = \text{Length}_{trk} - \text{Res}_{range}$ has been depicted in Figure 3.1.

Figure 3.2: $\frac{dE}{dx}$ vs Residual Range. There is a rise in the residual range in the region below 20 cm.
3.2 Energy Loss per Track Length for Pions

The following plots use the selection criterion on residual range at 20 cm, along with a selection criterion to ensure the $\frac{dE}{dx}$ and residual range value is not equal to zero. This is because at the end of the tracks there will be energy coming from more particle interaction which will effect the $\frac{dE}{dx}$ value. The following Figures 3.3 & 3.4 are without the space charge effect. The line used to fit these histograms has an almost zero gradient. Figure 3.4 includes a selection criterion on purity and completeness greater than 0.9. Therefore, the tracks being looked at are the best reconstructed tracks and help to de-convolute the SCE from some of the difficulties in reconstruction.

Figure 3.3: Energy Loss per Track Length vs Track length - Residual Range for Pions without space charge effect.

Figure 3.4: Energy loss per track length vs $T$ for pions including the selection criterion on purity and completeness without space charge effect.
The following Figures 3.5 & 3.6 also show the $\frac{dE}{dx}$ vs $T$ but the space charge effect has been included. The gradient of the fit of these histograms has increased and the intercept itself has also shifted. This should be a straight line if the space charge effect were to have no impact here. However, because of this shift even in Figure 3.6 where only the best quality tracks have been considered the identification of particles using their $\frac{dE}{dx}$ will be affected. The space charge effect will result in misidentification of particles using the $\frac{dE}{dx}$.

![Figure 3.5: Energy loss per track length vs $T$ for pions with the space charge effect.](image1)

![Figure 3.6: Energy loss per track length vs $T$ for pions including the selection criterion on purity and completeness with the space charge effect.](image2)
3.3 Energy Loss per Track length for Protons

To check whether the change in gradient found for pions also extends to other particles the $\frac{dE}{dx}$ vs $T$ for protons is shown in Figures 3.7 & 3.8. These two figures also include the selection criterion on purity and completeness so only the best quality tracks are being analysed here. As expected in Figure 3.7 the $\frac{dE}{dx}$ without the inclusion of the space charge effect has an approximately zero gradient. However, with the inclusion of the space charge effect in Figure 3.8 the gradient has increased and intercept shifted. Therefore, trying to use $\frac{dE}{dx}$ to identify particles will be problematic.

Figure 3.7: Energy loss per track length vs $T$ for protons including the selection criterion on purity and completeness without the space charge effect.

Figure 3.8: Energy loss per track length vs $T$ for protons including the selection criterion on purity and completeness with the space charge effect.
4 Conclusion

Many aspects of the pion cross section analysis are affected by the space charge effect. In the absence of a full space charge calibration some simple Monte-Carlo analysis can be used as a preliminary calibration. The reconstruction is shifted by the SCE and so the beam matching will also be affected. When matching from the reconstructed to true production point Figure 2.5 can be used. The difference between true and reconstructed start points in the $x$, $y$, and $z$ direction can be offset using the fit in Figure 2.7. Further work on calibration is needed for a correction when using $\frac{dE}{dx}$ to identify particles, which can be looked into in the future. If particles are wrongly identified this will affect the physics analysis when looking at the pion cross-section.
References


