# A novel method for event reconstruction in Liquid Argon Time Projection Chamber

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**Abstract.** Future experiments such as the Deep Underground Neutrino Experiment (DUNE) will use very large Liquid Argon Projection Chambers (LArTPC) containing tens of kilotons of cryogenic medium. To be able to utilize sensitive volume of that size, current design employs arrays of wire electrodes grouped in readout planes, arranged with a stereo angle. This leads to certain challenges for object reconstruction due to ambiguities inherent in such a scheme. We present a novel reconstruction method (named "Wirecell') inspired by principles used in tomography, which brings the LArTPC technology closer to its full potential.

## 1. Introduction

The new method of event reconstruction in Liquid Argon Time Projection Chamber (LArTPC) presented here is motivated by the stringent requirements of the DUNE experiment [1]. The DUNE primary science program [2] includes precision measurements of the parameters that govern neutrino oscillations, search for proton decay, and detection and measurement of the $\nu_\mathrm{e}$ flux from a core-collapse supernova in our galaxy. One of the central components of DUNE is a massive Far Detector (40kt fiducial volume) based on Liquid Argon Time Projection Chamber (LArTPC) located deep underground at a distance of 1,300 km from the neutrino source [3]. This device has the potential to reconstruct tracks and showers with high level of detail and efficiency, as well as to provide a precise measurement of ionization charge necessary for good particle identification based on ionization energy loss ($dE/dx$). The single-phase LArTPC design which is our focus here is an ionization chamber instrumented with planar arrays of wire electrodes [3].

## 2. Operation of the LArTPC with wire readout

### *2.1. Principle of Operation*

The LArTPC principle of operation is schematically illustrated in Fig.1. Ionization electrons are produced in the medium by ionizing particles associated with an event. Due to an electrostatic field maintained in the chamber, they start drifting to the right, while positive ions travel towards the cathode on the left hand side. The right-hand side of the diagram depicts planar arrays of sensor wires. Spacing between ajacent wires in a plane is of the scale of a few mm.

Just like any charge moving in the vicinity of a conductor, drifting electrons create signals on the wires belonging to the induction wire planes "U" and "V". When they finally reach the collection plane "Y" (where they are removed from the detector volume after completing their drift in the liquid argon medium), a signal is also produced on its wires. The ionization pattern can then be reconstructed in the plane perpendicular to the drift direction by analyzing signals on (U,V,Y), which form a stereo angle configuration illustrated in Fig.2 that is a schematic view of the three planes along the drift direction. The dot in the middle represents a localized ionization charge.

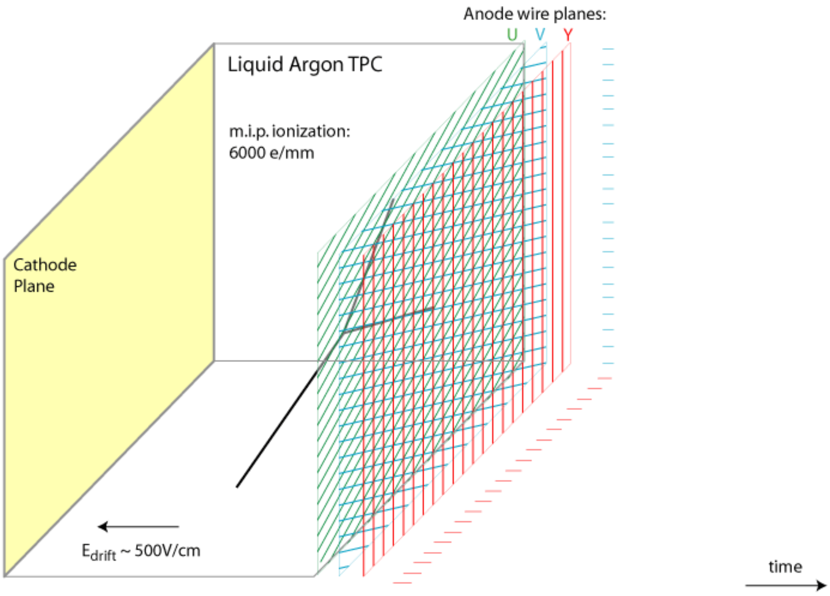


**Figure 1.** The LArTPC Principle of Operation

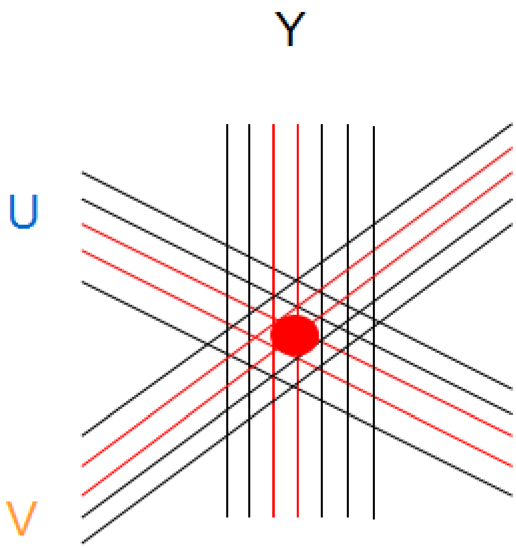


**Figure 2.** Collection and Induction Wire Planes as viewed along the drift direction

Every induction and collection wire is read out as an individual channel, with waveforms recorded at ∼2 MHz digitization frequency. There are also planar Cathode Plane Assemblies which are necessary to create a near-uniform electrostatic field in the chamber, however they are not instrumented.

Reconstruction along the axis of the drift direction can be done using the information contained in the time evolution of the signals on the (U,V,Y) wire planes, since each time bin corresponding to the ADC digitization cycle can be mapped to the coordinate in that direction, through the known (calibrated) value of drift velocity. In general, signals on individual wires produce complex waveforms, and are subject to electronics noise, shaping parameters in the amplifier chain and other factors. Evaluating the charge in a particular time bin involves complex signal processing, and is beyond the scope of this paper (see [4] for a few details).

### *2.2. The Challenge*
It is not difficult to see that while the wire readout design makes construction of very large LArTPCs possible by keeping the channel count within practical limits, it does so at the cost of information loss, since now instead of pads or pixels one has to reconstruct the position of the particle "hits" in 2D using three projections. If the number of sensor wires that registered a signal is $\sim$N, the number of potential hit locations scales as $\sim N^2$, which naturally leads to ambiguities.

## 3. The "Wirecell" method
### *3.1. Reconstruction in LArTPC*
Event reconstruction in LArTPCs with wire readout is primarily geared towards neutrino interactions with multiple final state particles emerging from a single vertex. Reconstruction methods which existed prior to introduction of the method described in this paper were inspired by tracking algorithms utilized in High Energy Physics, and indeed reused existing software libraries in some cases. A typical approach starts with identifying track candidates in each of the three projections which were described above. This is done by identifying groups of wires in each projection which had "hits" is adjacent time bins, effectively relying on the continuity of the object being reconstructed at this stage in the reconstruction process. Hypotheses are applied regarding whether the object corresponds to a track or to a shower. Then, an attempt is made to match individual 2D (time-coordinate) projections in 3D [5]. As mentioned in 2.2, there are ambiguities in this process which may result in reconstruction artifacts.

### *3.2. Parallels to Tomography*
The method of collecting signals from LArTPC has parallels with Computerized Axial Tomography (CAT) applications. Each time slice in LArTPC is read out separately and effectively represents a separate unit of data. This can be compared to one of the original (and simplest) methods of CAT called Multiplanar Reconstruction – MPR – in which the volume under study is treated as a stack of 2D slices. Revisiting Fig.2 one can see that the same charge pattern in an individual 2D slice is sampled in three different projections. Each wire is measuring a line integral of the ionization charge located in its vicinity. This has significant similarity to absorption tomography where attenuation of radiation intensity also corresponds to a line integral along the direction of the beam. Clearly, the number of projections is extremely limited (to three) which makes application of mainstream CAT reconstruction techniques such as Radon transform [6] not practical. It must be noted however that sparse and limited-angle tomography does have its applications and domain-specific mathematical methods have been developed to deal with such extremely ill-posed problems.

CAT applications typically feature voxelization of the object under study due to natural granularity of the apparatus and also to make numerical calculations feasible. In multiplanar reconstruction, this effectively leads to treating each individual 2D slice as a set of pixels, defined according to the type of measurement. Application of this technique (introduction of cells) is the foundation of the Wirecell method for LArTPC described here [7].

*3.3. The "Wirecell" algorithm*

The term "time slice" is used here to describe data (signal values) belonging to a single time bin – a single digitization cycle of the ADCs processing the signals from wire planes. These data contain information about what is essentially a 2D image (a slice of the 3D object under study). In Wirecell, a tessellation algorithm is used to describe each time slice as a set of polygon pixels in 2D. Each wire is associated with a subset of pixels. Reconstruction is done in two steps:

- Solving the inverse problem in each time slice, i.e. performing 2D imaging (reconstructing pixel values) using the three projections of the charge distribution in the time slice.
- Combining the time slices to obtain a 3D model of the ionization pattern in the Liquid Argon Volume, which can then be used to extract physics information about the event.

The inverse problem of determining pixel charge values based on limited number of projections (three sets of wires) is ill-posed. Therefore, the following algorithm is applied which helps to reduce the number of degrees of freedom: groups of adjacent candidate cells with signal above a certain threshold are identified. They are grouped into "merged cells" (i.e. the charge values are combined to effectively form a *larger pixel*). Note that many of these cells will still be ghosts due to ambiguities as described above (see 2.2). Wires mapped to these merged cells are also merged.

Note that the values of charge in "merged cells" are not known as a result of a direct measurement and need to be computed, based on the values of signals on "merged wires" (groups of adjacent wires that registered signals). The relationship between the wires and cells can be represented as $W_m = G\,C_m$, where $W_m$ is the vector of values attributed to charges on merged wires (measured directly), $G$ is the geometry matrix mapping wires to cells, and the $C_m$ is the vector of values for merged cells, for which a solution must be found. In vast majority of cases this cannot be solved by matrix inversion. Instead, the Wirecell method employs the Markov Chain Monte Carlo (MCMC) approach, which aims to minimize the following value:

$$\chi^2 = (W_m - GC_m)^T V^{-1} (W_m - GC_m)$$

$V$ stands for the covariance matrix for signals on merged wires. Each step in the MCMC process involves removing a random cell and recalculating $G$ to evaluate the metric as described above. If the $\chi^2$ value improves, such cell is permanently eliminated under the hypothesis that it was a "ghost cell". Once a sufficient number of cells have been eliminated, matrix inversion becomes possible which completes the solution. A reconstructed 2D image is formed, and a stack of these images forms the 3D picture of the physics event in LArTPC. It is important to note that in this method, no physics assumptions are made either about the type of particle or the number of tracks in the event before the event is assembled in 3D.

The optimization technique as described above can be modified to take advantage of certain apriori information about the object, which is another common approach in the field of tomography. For example the hypothesis of object continuity in 3D can be included in the solution by adding a penalty value to $\chi^2$ in cases there there are no active cells in neighboring 2D slices, adjacent to the one being considered for elimination during the MCMC step.

The Wirecell algorithm contains a number of elements which are computationally intensive, e.g. each step in the Markov Chain involves recalculating matrices and other operations. For that reason, work is currently under way to adapt Wirecell for use on modern parallel computing platforms, including GPUs.

*3.4. Status and future directions*

The Wirecell method has been applied to reconstruction of a variety of event classes using Monte Carlo data. In the first round of analysis, efficiency of track reconstruction in this method is at or above the levels stipulated by the requirements of the DUNE experiment. It is currently being adapted for event reconstruction in the $\mu$BooNE experiment [8], and results are expected to become available soon.

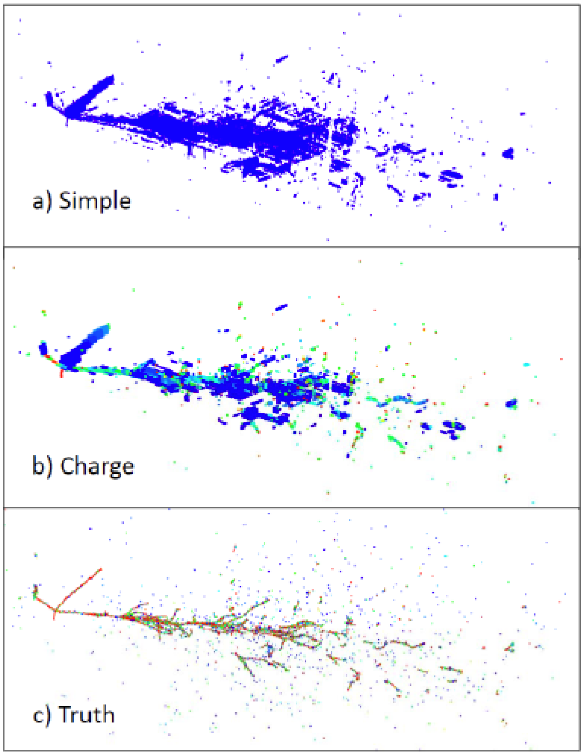


**Figure 3.** Comparison of hit-based reconstruction ("simple"), Wirecell ("charge") and MC Truth ("truth"). Blue color in (a) and (b) represents the reconstructed charge density distribution. Note the improvement from (a) to (b).

## 4. Summary

A novel reconstruction method has been developed which applies tomography principles to neutrino event reconstruction in Liquid Argon Time Projection Chambers with wire readout. Markov Chain Monte Carlo technique is used for the inverse problem solution in 2D, with a full 3D image formed as a stack of 2D slices. First results are promising and indicate that this method can bring the LArTPC technology closer to its full potential for physics research.

## References


[1] DUNE CDR Vol 1 – The LBNF and DUNE Projects: `http://arxiv.org/abs/1601.05471`

[2] DUNE CDR Vol 2 – The Physics Program for DUNE at LBNF: `http://arxiv.org/abs/1512.06148`

[3] DUNE CDR Vol 4 – The DUNE Detectors at LBNF: `http://arxiv.org/abs/1601.02984`

[4] $\mu$BooNE public notes 1016 and 1017

[5] F. Arneodo et al. (The ICARUS-Milano Collaboration) "Performance Of A Liquid Argon Time Projection Chamber Exposed To The WANF Neutrino Beam", Phys.Rev.D74:112001,2006

[6] William H. Press, " Discrete Radon transform has an exact, fast inverse and generalizes to operations other than sums along lines", Proceedings of the National Academy of Sciences of the United States of America, 1924919254, doi: 10.1073/pnas.0609228103

[7] Wirecell: `http://www.phy.bnl.gov/wire-cell/`

[8] $\mu$BooNE experiment: `http://www-microboone.fnal.gov`