

Why a Liquid Argon Detector is the correct technology choice for LBNE

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The Long Baseline Neutrino Experiment (LBNE) represents an ambitious, compelling program for the exploration of key questions at the forefront of particle physics. Chief among the discovery opportunities it will enable are searches for violations of CP symmetry in neutrino oscillations, searches for nucleon decay, and studies of neutrino bursts from locally occurring supernovae. The conceptual design phase of LBNE has produced a design for a Far Detector option based on the Liquid Argon Time Projection Chamber (LArTPC) technique, which provides a unique opportunity to construct a scalable, cost-effective, massive detector with exquisite performance capabilities.

While many arguments can be made for selecting an LArTPC as the far detector for LBNE, the following reasons are why we believe that it is the correct instrument for the LBNE from the standpoint of the science program:

- For the LBNE neutrino beam physics the LArTPC is superior because no other viable detector has better efficiency and background rejection capabilities.
- For proton decay searches the LArTPC offers the ability to probe important channels with a sensitivity not available to any other detector. Considering existing and projected experimental constraints from SuperKamiokande, which is becoming background-limited in key modes, the LBNE LAr detector being proposed is unique in its potential for discovery.

- If a supernova occurs within our galaxy during LBNE detector operation, an LArTPC offers the opportunity to detect the neutrinos in a mode complementary to existing or proposed water Cherenkov detectors

An external review committee that was asked to assess the science capabilities of both a water Cherenkov and liquid argon TPC for LBNE further reinforced these reasons, stating in their final conclusions: “The committee unanimously agrees that, on the question of scientific capabilities, that the prospect for the LAr detector to refine our understanding of neutrino oscillations, and to be sensitive to unexpected new physics, exceeds that from the WC detector” [4].

The purpose of this document is to present a brief description of key features of the LArTPC option for LBNE. It is intended as a reference for those wanting an overview of the capabilities of the proposed detector, and of the primary arguments for why it is the correct technology choice for LBNE. For more detail, we refer the reader to the “LBNE Case Study Report: Liquid Argon TPC Far Detector”[1], which focuses on the science reach, as well as volume 5 of the LBNE Conceptual Design Report,[2] which provides technical detail on the detector design.

The LBNE Baseline and Beam Spectrum

A program of measuring long-baseline neutrino oscillations has been operating in the U.S. since the MINOS experiment began taking data in 2005. MINOS has made significant high precision measurements of several oscillation parameters and continues to take data. Using the same neutrino beam as MINOS, the NOvA experiment located at Ash River, Minnesota, 810 km from Fermilab, will begin operation in 2013. NOvA will measure ν_e appearance and have the first opportunity to determine the neutrino mass hierarchy for certain regions of the neutrino oscillation parameter space. The ultimate physics reach of the NOvA experiment however will be inherently limited due to the length of the baseline. The opportunity to develop the Homestake Mine in Lead, South Dakota as a deep underground laboratory for science provides a solution to the baseline problem. The distance between Fermilab and the Homestake Mine is 1300 km, which enables us to measure both the mass hierarchy and CP violation with high precision in the same experiment. The LBNE wide band beam is designed to produce neutrinos ranging in energy from 0.5-6.0 GeV and is hence optimized to

cover the region of oscillations for a 1300km baseline. The capability of an LArTPC detector is well matched to this energy regime.

Detector Performance

The LArTPC detector technology provides LBNE with exceptional capabilities, directly suited to the physics goals of the experiment. The measurement of position and energy deposition on millimeter-scale 3-D space point coordinates along the full length of charged-particle trajectories underlie the exquisite event reconstruction and calorimetric capabilities of the LArTPC. Signatures from processes of interest, such as inclusive ν_e interactions and exclusive proton decay channels, can be studied in detail, and pernicious backgrounds can be identified and rejected.

As pertains to the ν_e appearance physics, the key requirements are the identification with high efficiency of the electromagnetic shower associated with the outgoing electron in charged-current interactions, and in particular the ability to distinguish such electrons from photons produced in neutral-current interactions. This is achieved through topological and calorimetric signatures. In the first centimeters of travel, *i.e.*, prior to the initiation of the shower, the ionization signal is at the 1-MIP level for electrons, while for photons there is a gap between the production point and the first pair-production event, at which point the ionization signal is at the 2-MIP level. Using this information, an LArTPC can uniquely separate electrons from photons, a critical component in being able to distinguish CC ν_e signal events from NC π^0 and NC γ backgrounds.

The granularity and energy resolution provided by an LArTPC satisfies the long-baseline physics requirements: even in the case of inelastic ν_e interactions, the detection efficiency remains high – greater than 80% according to event scanning studies and analyses carried out for a number of considered long-baseline experiments. The ν_e identification efficiency is flat over a broad range of energies which makes the detector well suited for a variety of beam designs.

The analysis of data in a large LArTPC began in ICARUS ten years ago with cosmic ray tests at Pavia. Good topological event discrimination and excellent energy resolution were demonstrated. Figure 1a shows a single event picture of a hadronic interaction with a π^0 , and Figure 1b shows the 2γ

invariant mass distribution for π^0 candidates. (This distribution gives a 37 MeV mass resolution, and corresponds to a sample with mean π^0 energy of 700 MeV, including events with considerable hadronic activity; better resolution is achieved for more topologically isolated signatures.)

From detailed Monte Carlo studies, ICARUS has determined the electromagnetic energy resolution to be $3\%/[E \text{ (GeV)}]^{1/2}$ for intermediate-energy single electrons, and $11\%/[E \text{ (MeV)}]^{1/2} + 2\%$ for electrons below 50 MeV. Performance studies with ArgoNeuT data are in progress and present indications support the performance metrics obtained by ICARUS. The first physics results from ArgoNeuT have been submitted for publication.

Some simple examples to illustrate the advantages of a LArTPC far detector are shown in Figures 2a and 2b. The first image is an event picture of an asymmetric π^0 decay (photon energies 342 and 48 MeV) and the second is of a π^0 decay with two photons emitted with a small opening angle. Both are classes of events that are most frequently mis-identified as potential ν_e signals in a water Cherenkov detector, but can be clearly rejected as background events in an LAr TPC due to the fine granularity of the detector.

LBNE sensitivity studies for ν_e appearance physics indicate that the exceptional capabilities of LArTPC performance give a mass advantage factor of approximately 6 – that is, a 200-kiloton (fiducial) water Cherenkov detector has roughly the same sensitivity to this physics as a 33-kiloton (fiducial) LArTPC.

Similarly, for proton decay searches, the required capabilities include particle identification via dE/dx (i.e., identification of the kaon in the $p \rightarrow K\nu$ channel), topological/kinematic reconstruction of multi-particle final states and rejection of cosmic ray spallation-induced backgrounds. The design goal of the LArTPC detector system is to keep the background rates below one event for a long running period for essentially all decay modes, to avoid ever approaching the background-limited regime.

Beyond the question of sensitivity to GeV-scale physics, it is expected that the LBNE LArTPC will also excel at physics at the few 10's of MeV, required for studies of neutrino bursts from nearby supernovae. To meet this goal, the TPC readout system is designed to keep noise and nuclear decay signals below a level of one-half a minimum ionizing particle on each

readout wire. This corresponds to about one MeV, and should allow local triggers at a level of a few MeV. Additionally the light detection system for the LBNE LArTPC will be sensitive to scintillation photons from events with visible energies as low as 10 MeV throughout the detector. While photon detection is likely not essential for triggering, it will be useful for providing t-zero information to facilitate attenuation corrections for the ionization signals.

In summary, the expected performance of LArTPC's has a broad dynamic range and has been validated through detailed Monte Carlo studies in the context of multiple experiments, as well as through analyses of real data in the case of ICARUS and ArgoNeuT.

The Near Detector

Effective utilization of a near detector in an oscillation experiment requires a number of steps, including estimation of the true neutrino spectrum from the observed near detector spectrum and its converse at the far detector. These estimations are subject to uncertainties – and it is desirable that they cancel to the extent possible. By far the best and least model-dependent way to obtain maximum cancellation is if the near and far detector are identical in terms of target materials, detector segmentation, and resolution. A liquid argon detector allows a compact and well-understood way to achieve this, and allows the possibility of magnetization of the near detector if desired. Since near/far estimates in an intense beam can be made from appropriate subsamples of the near detector data, the ability to turn a field on and off, or to reverse it, gives critical information about the behavior of the beam and detector without losing the ability to do the direct comparisons at the heart of the method.

Extracting the oscillation parameters for the mass hierarchy and CP violation from the observed event spectra will require that systematic uncertainties are controlled to high precision. This is especially true in the event that θ_{13} is large (the neutrino/antineutrino asymmetry one is trying to measure becomes increasingly small as θ_{13} increases). Operating an identical detector at the near site is a significant advantage. To be successful, the oscillation analysis requires tight control over both the projected background rate and the absolute efficiency for rejecting background events in the far detector. The latter is a particularly challenging uncertainty to quantify. In the case of LAr,

similar algorithms can be applied to the near and far detector data to explicitly assess detection efficiency uncertainties. In this way, LAr has the potential advantage of operating a near detector that is both fine-grained (to better study the background sources, ala T2K) and functionally identical (to cancel detector effects, ala MINOS and NOvA). Hence, LAr can uniquely enable both the T2K and MINOS/NOvA-style near detector strategies. These combined capabilities will be crucial in ensuring the reliable extraction of such subtle effects as CP violation from the observed data.

A New Technology

One of the hallmarks of experimental high energy physics is the innovation it inspires in order to meet the challenges required by the scientific goals. It is this ability to be creative and innovative that encourages bright young people to enter the field. In the past this innovation has also benefited society at large, leading to novel cancer treatments and medical imaging techniques. The LBNE LArTPC would continue this tradition of innovation with the opportunity to push a detector technology to a new level. Moreover, the high spatial resolution of this technology places LBNE in a position to find the unexpected, as nature occasionally rewards versatile detectors that happen to be well positioned to observe unexpected signatures of new physics.

While the use of LArTPCs for multi-kiloton scale detectors is new, the engineering for such devices is well understood. The use of membrane cryostat technology has 1600 tank-years of service in more demanding applications, such as the storage and transportation of liquid natural gas. The 600 ton ICARUS detector has shown that the technology can be used effectively and safely for neutrino detection in an underground environment. In addition we have made major advances here at FNAL in understanding how to operate liquid argon systems, including the successful ArgoNeuT and LAPD runs. The recent review of the LBNE far site concluded that "based on such successes as ICARUS, ArgoNeuT and the recent LAPD results, there is no doubt that a large liquid argon TPC can be deployed and have a rich physics program." [3]

Staged Development Plan

The integrated program to successfully construct and operate a large-scale LAr TPC has been developed with a staged approach that will build

confidence and allow us to improve the design at each step, if necessary. The staged program in the U.S. began in 2006 with the Yale TPC and the FNAL Bo TPC, each with 0.02 tons active mass. These were soon followed by the larger 0.3 ton ArgoNeuT detector which collected neutrino data in the NuMI beamline from 2009-2010. Many lessons were also learned from the development program for the 600-ton ICARUS detector. The next major step in the U.S. is the larger ~ 100 ton MicroBooNE detector, which will be assembled in 2012 and begin data-taking at the end of 2013. In parallel, efforts are underway to further our understanding of the requirements for achieving the necessary level of argon purity and to confirm the use of non-evacuated cryostats; LAPD is currently operating, and the 35-ton membrane cryostat will be operated in 2012. The LAr1 engineering prototype will provide an integration test bed in addition to serving as a visible demonstration of LAr TPC technology in the U.S. Implementation of small scale LArTPCs in the Fermilab test beam will provide calibration data and offer an opportunity for young collaborators to gain hardware and data-taking experience. We also note, that this technology, pioneered primarily in Europe, provides a promising opportunity for international collaboration for both the near and far term programs.

The LAr20 modules for LBNE will be the ultimate stage, with its well-developed conceptual design built upon the knowledge gained by building and operating smaller predecessors in the U.S. and Europe.

Just as the high efficiency for ν_e identification in the LAr detector drives the required mass ratio between the WC and LAr detectors, the same argument holds when comparing the performance of a liquid argon detector to the NOvA liquid scintillator detector. In this case the ratio is more like ($\sim 1:3$) implying that a 5kT LAr detector located in the NuMI off-axis beam at Ash River could statistically enhance the physics results from NOvA. While this is not an ideal step in the evolution of the neutrino oscillation program it warrants consideration in the face of severe fiscal constraints.

In addition to increasing our confidence in large scale LArTPC construction, we will also maximize our use of the existing data. The wealth of ArgoNeuT data taken in a neutrino beam is providing the young scientists working on it the experience necessary to tackle the next LArTPC experiments like MicroBooNE and LAr1. Over the next decade, each one of these experiments will provide experience in exploiting the data and refining the reconstruction techniques, such that there will be a community ready to

analyze LBNE data as soon as the detector is commissioned. Additionally, these scientists will be producing useful physics results and associated publications throughout the period leading up to the construction of LBNE.

Modular Implementation

The current design for LAr40 at the 4850 level is for two 20-kT modules, each with a fiducial mass of 16.3-kT, giving a total fiducial mass of 33-kton. A LAr far detector offers the flexibility of staging detector construction in smaller modules if funding for the experiment is significantly reduced or delayed.

Depth Considerations

A 33-kton LAr TPC installed at the 4850' level at Homestake enables a rich physics program including (1) beam oscillation physics, (2) unique capabilities for proton decay and (3) sensitivity to galactic supernova bursts. No active veto shield is needed at this depth. The LAr technology can also be adapted to provide a competitive program at relatively shallow depths. Beam oscillation physics as specified by the CD-0 Mission Need for LBNE can be accomplished with a modest overburden. For other physics, a LAr detector at moderate depth (i.e. 800' level) can be supplemented with an active veto shield and an internal trigger system to enable the science.

Value Engineering Opportunities

In the LAr40 design, each detector module consists of 3 wide x 2 high x 18 long independent drift cells. The length of each detector module can be readily changed to match funding constraints or opportunities with minor design changes. For example, adding a 3 wide x 2 high x 1 long set of drift cells to each detector module would increase the fiducial mass by 2 kton for a cost of ~\$15M.

Significant cost savings were identified in an initial Value Engineering exercise for the 4850' option by moving the cavern into the better known Yates rock formation, transferring argon in the gas phase in the Yates shaft thereby eliminating the need to rehabilitate the Oro Hondo shaft, and by placing the nitrogen compressors on the surface. Additional cost savings may be identified after further investigation.

Schedule

Implementation of a new technology takes time and patience. A carefully planned development program can proceed in stages, with each piece being affordable on a few years time scale. In the current budgetary climate, it is likely that fiscal constraints on the funding will delay project construction more so than the technical development stages. Development stages that also yield scientific results and training opportunities offer a solution to the long time scale required to accrue the funding for mega-scale projects.

Conclusion

In summary we believe that the choice of the LArTPC for the LBNE far detector is the option which provides the best opportunity to achieve the most important science goals of the experiment, advance a new technology and provide a staged active experimental development program beginning now and extending into the next decades.

References

- [1] LAr Case Study Document : <http://lbne2-docdb.fnal.gov:8080/cgi-bin/DocumentDatabase/, docdb#3600>
- [2] Conceptual Design Report for the LBNE Liquid Argon Detector : <https://wiki.bnl.gov/dusel/index.php/CDR : Volume5>
- [3] Far Site Internal Conceptual Design 2011 Closeout Report : <http://lbne2-docdb.fnal.gov:8080/cgi-bin/DocumentDatabase/, docdb#5242>
- [4] Science Capability Review Final Report : <http://lbne2-docdb.fnal.gov:8080/cgi-bin/DocumentDatabase/, docdb#5333>

Figures

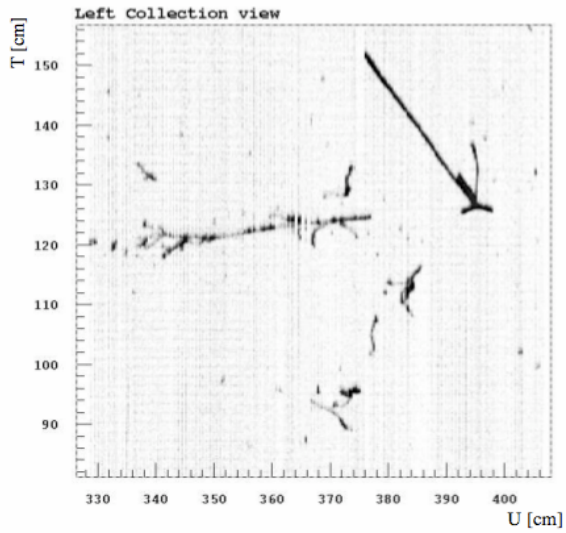


Figure 1a

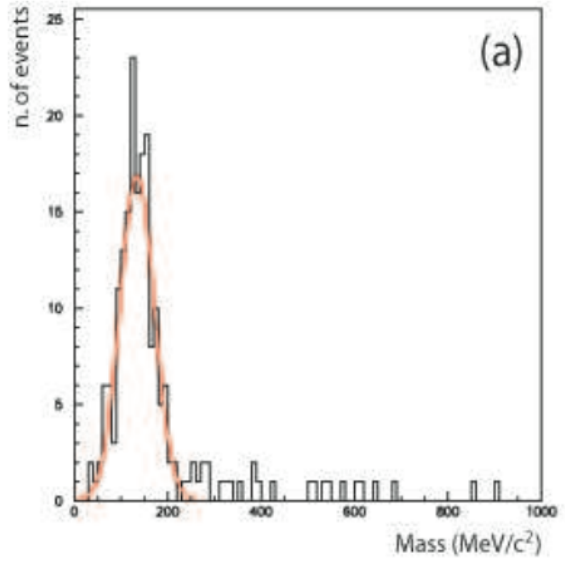


Figure 1b

Figure 1 (a) a single event picture of a hadronic interaction with a π^0 in the ICARUS detector and (b) the 2γ invariant mass distribution for π^0 candidates

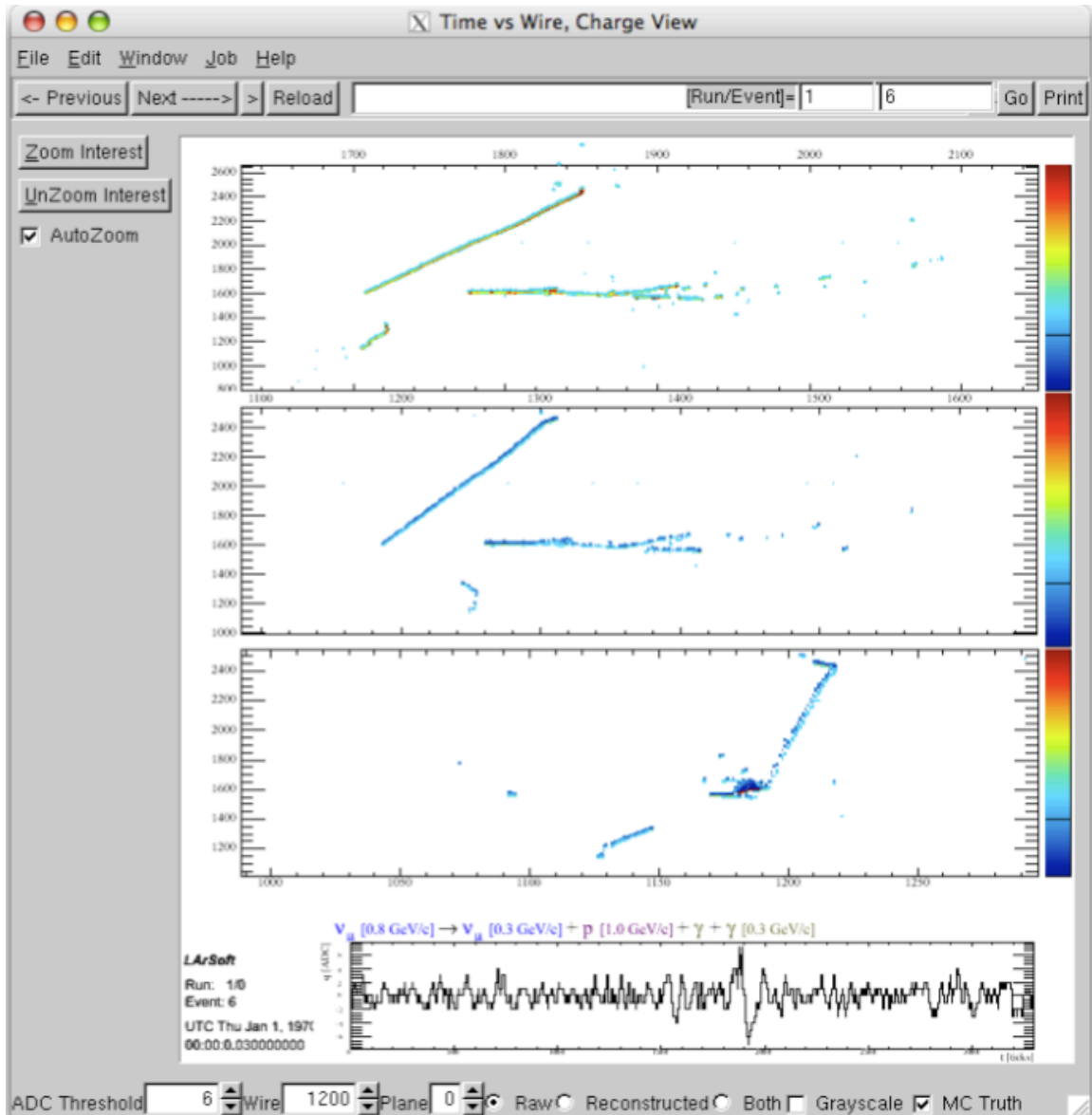


Figure 2a: An example of a common class of NC events (one containing an asymmetric π^0 decay) that can be frequently mis-classified in a WC detector but identified in a LAr TPC. Even when one of the photons from the π^0 decay is very low in energy, it can still be observed and identified as a background event in a LAr TPC. There are two clear photons seen in this event. This specific event was mis-classified as being ν_e in a Super-K simulation.

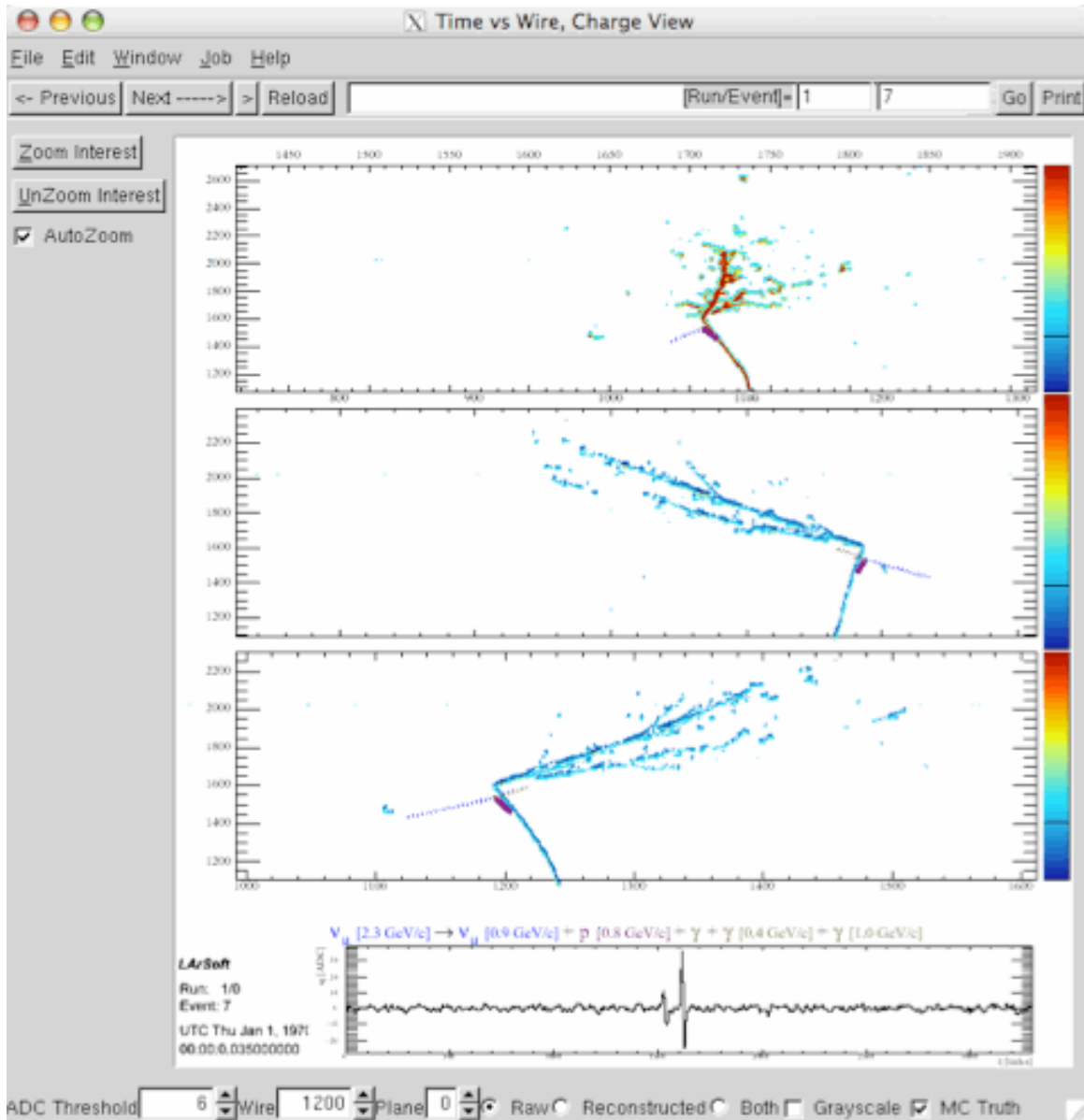


Figure 2b: An example of a common class of NC events (one containing a high momentum π^0 decaying to two photons with a small opening angle) that can be frequently mis-classified in a WC detector but identified in a LAr TPC. The two photons from the π^0 decay can be clearly identified in a LAr TPC even if they are emitted with a small opening angle. This specific event was mis-classified as being ν_e in a Super-K simulation.