Measuring the Neutrino Event Time in Liquid Argon by a Post-Reconstruction One-parameter Fit

A White Paper for Snowmass 2021

March 21, 2020

E. Angelico, H. J. Frisch,
Enrico Fermi Institute, the University of Chicago
M. Wetstein
Iowa State University

Abstract

We propose a relatively simple method to measure the event time in liquid Argon (LAr) TPC-based neutrino detectors that takes advantage of the topological reconstruction of each event from the TPC data prior to performing a 'one-parameter' fit. Measured times and positions of detected photons are fit to simulated Cherenkov light from the reconstructed tracks, treating the event as a rigid body with only the neutrino interaction time as a free parameter. Chromatic dispersion and other effects can be addressed by limiting the fit to simulated photons in a selected range of wavelengths and/or from specific parent tracks. A back-of-the-envelope calculation predicts that the method results in a significantly lower photodetector coverage than needed for the same precision in conventional warm-liquid detectors.

1 Introduction

The proposal to rebunch the Main Injector beam on a higher RF harmonic [1] would allow both the LBNF Near and Far detectors [2] to see the full on-axis fluxes binned by neutrino arrival time. Each time bin serves as a contemporaneous Far/Near-detector oscillation experiment with its own characteristic flux spectrum selected on the neutrino time-of-arrival. However, instrumenting the Far detector with fast timing has been regarded as daunting due to the number of photo-detectors required for large fractional coverage. Here we describe a method that exploits an inherent advantage of TPC-based LAr detectors over large warm-liquid neutrino detectors to substantially reduce the required coverage for extracting the event interaction time at the needed precision.

The organization of this White Paper, intended as input to Snowmass 2021, is as follows. Section 2 recapitulates the 'Stroboscopic' proposal for exploiting the correlation of true neutrino energy with the detected neutrino time-of-arrival by rebunching the Main Injector beam on a high RF harmonic [1]. Section 3 gives a brief introduction to the necessary '4D-precision photo-detection', here defined as the simultaneous measurement of photon arrival with a time resolution of tens of picoseconds and a space resolution of several millimeters. The post-reconstruction generation of Cherenkov light from the simulation of the charged tracks reconstructed by the LAr TPC is described in Section 4. Section 5 describes the 1-parameter fit of the time/space coordinates of the simulated photons to the coordinates of the detected photons for the neutrino event time. Determining the photodetector coverage needed to identify the neutrino time bin, including the use of mirrors to extend cathode coverage, is briefly discussed in Section 6. Section 7 presents conclusions.

2 The Stroboscopic Method

The Fermilab-Chicago Timing Planning Meeting workshop [3] was held in March, 2018 to discuss what currently inaccessible physics one could do with 'precision-4D' measurements [4]. The discussion led to a proposal to rebunch the Main Injector beam on the 10th harmonic of the current RF frequency, 531 MHz, to produce shorter proton bunches [1]. Although the 120 GeV protons and the neutrinos are ultra-relativistic, the difference in the velocity of the parent hadrons from $c = 1$ leads to a correlation of the arrival time of neutrinos at both the Near and Far detectors with energy. In November 2019, Fermilab, Chicago, and Iowa State held a second meeting at Fermilab, the Workshop on Precision Time Structure in On-Axis Neutrino Beams [5, 6], to vet details with accelerator and neutrino detector experts.

The left-hand panel of Figure 1 shows the momentum spread in one bunch of the current 53 MHz Main Injector beam versus the phase in nanoseconds in red, and the same for the beam rebunched on the 10th harmonic in blue [1]. The right-hand panel shows the neutrino momentum spectra in 200 psec bins of time of arrival relative to the proton bunch assuming a 100 psec detector resolution and a 250 psec proton bunch width. The late-arrival bins have a much softer distribution in neutrino energy than the early-arrival bins.

The beauty of this is in the correlation of true neutrino energy with an observable unrelated to the neutrino energy as measured in the detector. Each time bin serves as a contemporaneous experiment, viewing the identical detector, and undergoing the identical identification of electron appearance, muon CC and NC events, tau neutrinos, and other signatures, but with its own characteristic neutrino flux versus energy.

The Stroboscopic proposal [1] allows both the Near and Far detectors to see the full on-axis time-energy correlated fluxes contemporaneously. However, instrumenting the Far detector with fast timing has been regarded as daunting due to the number of phototubes required for large fractional coverage. Here we present a method that exploits the advantages of LAr to substantially reduce the required coverage for extracting the event interaction time at the needed precision.

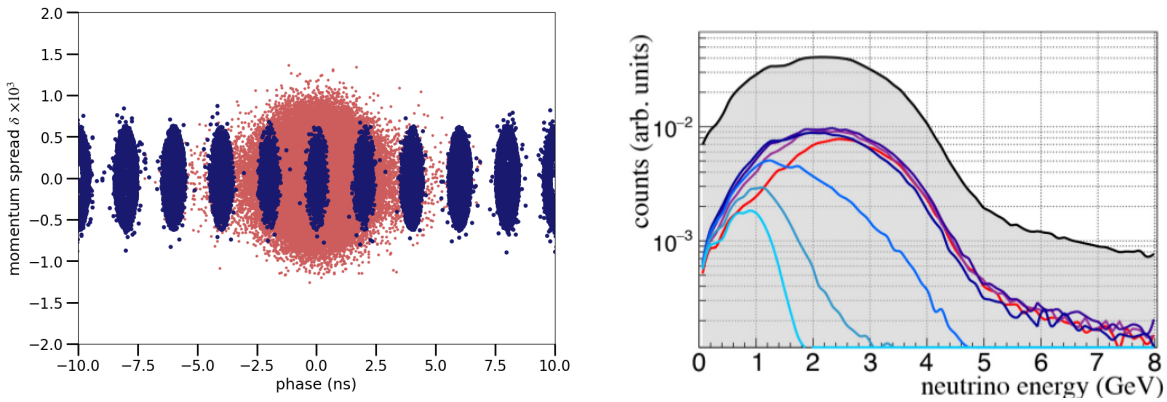

Figure 1: Left: the momentum spread for one bunch of the current 53 MHz Main Injector beam versus the phase in nanoseconds (Red), and for the beam rebunched on the 10th harmonic (Blue). Right: the neutrino momentum spectra in 200 psec bins of time of arrival relative to the proton bunch assuming a 100 psec detector resolution and a 250 psec proton bunch width.

3 Large-Area High Space/Time-Resolution Photo-detection

The capability of simultaneously measuring the position of a charged particle or photon and the time of arrival at a precision comparable to light travel times of a millimeter, dubbed 'Precision-4D', enables imaging of the event topology from photon travel times given enough detected light. Systems of Silicon Photomultipliers (SiPMs) or MCP-based photomultipliers (MCP-PMTs) such as the Incom LAPPD [7] would provide adequate time and space resolution for exploiting the time-energy correlation. A possible electronics architecture for the precision-4D photodetector consists of a multi-buffer waveform sampling front end [8] with an effective buffer length long-enough to accommodate the DUNE trigger latency [9].

Time at the Near and Far detector locations [10] and bunch-by-bunch at the production target would be recorded relative to a master clock distributed via a system such as White Rabbit [11]. Synchronization among these three locations at the required level is within the capabilities of current technology [12]. The requirements for clock distribution within to the photo-detectors within each of the Near and Far detectors are within the capabilities of the current system at the Fermilab TestBeam Facility.

We note that the determination of event time is done after the event has triggered and has been reconstructed, requiring no changes to the current plans for the optical detector system for scintillation light or triggering.

4 Simulation of Cherenkov Photons from the Reconstructed LAr TPC Data

The reconstruction of the event time in large warm-liquid detectors such as JUNO [13] and Hyper-Kamiokande [14] requires a photodetector coverage approaching unity for reconstructing the topology and locating the event vertex from Cherenkov light, as well as for good energy resolution [15, 16, 17]. For a detector the size of the DUNE Far detector, the photodetector cost and scope of the detector upgrades would be unmanageable. In addition, the inherent reconstruction resolution is poor. Chromatic dispersion and scattering complicate the picture; both hardware and software schemes can mitigate the effects, but there is a net information loss leading to a time resolution comparable or larger than needed for the stroboscopic timing in the Far detector. For many reasons instrumenting the Far detector in DUNE with Precision 4D for event reconstruction has been considered a non-starter [5].

However, the need for photodetector coverage in a LAr detector is different from that in conventional large warm-liquid detectors in that the TPC provides a full precise topological reconstruction of the event. Here we propose adding a dedicated sparse system of photo-detectors with cm-scale time and space resolution [18] to record photons from Cherenkov light from the charged tracks in the event. The output from the LAr event reconstruction of the TPC data is used as input to a simulation that generates Cherenkov light from reconstructed tracks. The simulated photons are propagated to the detector inner surfaces where position and associated time-of-arrival (hits) are recorded. The predicted 4D 'hits'– the time of photon arrival and associated position– are then compared to the measured time-of-arrival and position of the measured hits. A measure of goodness-of-fit plotted versus time yields a best-fit to the neutrino interaction time and its uncertainty.

4.1 The Event as a Rigid Body

The precision of the reconstructed topology of a neutrino event in a very large LAr detector is expected to be a few mm [19], i.e. on the order of 10 psec light travel time [18]. This is small compared to the Stroboscopic time binning [1]. The reconstructed event thus can be considered a 'rigid body' in the classical sense, i.e. having no internal degrees of freedom (DOF) on the scale needed for event time reconstruction. At the required precision the 6 DOFs of event position and orientation also should be adequately measured [19] after corrections.

4.2 Simulating the time and position of Cherenkov photons from the LAr data after TPC reconstruction

The tracks in the reconstructed event provide input to a fast simulation to generate Cherenkov photons. The photons are then propagated to the detector surfaces and position and time relative to the primary neutrino vertex are recorded. Additional truth information such as photon wave-length, polarization, and scattering history is also recorded.

5 The Post-Reconstruction One-parameter Fit

5.1 Fitting the observed 4D hit list to the simulated LAr hit list

The position and time for Cherenkov photons generated by the simulation from the reconstructed tracks will depend on the time of the event. For efficiency not all Cherenkov photons need to be simulated; the generation may be limited to tracks only above some momentum, length, or angle. The uncertainties in time and position of the simulated photons may be parametric, depending on photon drift length, wavelength, direct or reflected, and possibly event type and topology.

The two lists, measured and simulated, are then compared in a 1-parameter fit, for example a simple χ^2 fit versus event time. Not all generated Cherenkov photons will have a match, nor will all measured photons have a match within the estimated error. Both the number of matches and the goodness-of-fit enter into the determination of the event time.

5.2 Chromatic dispersion, Absorption, and Polarization

The list of predicted hits and tracks used for fitting the measured data can be curated; not all emitted Cherenkov photons need to used in the comparison. For example, an initial fit could use only simulated photons in a limited wavelength range to minimize dispersion. After the fit, other, un-matched hits, can be fit as a function of wavelength to measure chromaticity. Similar information on photon scattering, absorption, and polarization, for example, can be extracted from the data by selecting on photon optical paths.

6 Photodetector Coverage

The desired precision on the event time determines the photodetector coverage. Both the distribution of photodetector modules and the overall fractional coverage need to be opti-

mized. A given 'tiling' of the detector surfaces with photo-detectors yields the number of matched hits versus event time. The match rate versus coverage informs the scope of the required coverage.

6.1 The Use of Mirrors and the Optical Time Projection Chamber

Precision-4D detectors allow mirrors to multiply photocathode coverage by using the drift time of photons to constrain the path-length travelled from the source for both direct and reflected photons. Figure 2 describes the use of mirrors in a small Optical TPC, which was tested in the Fermilab MCenter test beam [20, 21]. The left-hand panel shows the concept. A plastic tube filled with water provides Cherenkov radiation for particles travelling down the tube; five Planacon [22] MCPs detect the light in a 30-degree stereo configuration, with each MCP providing 30 points along the track via a micro-strip anode. Planar mirrors on the opposite side of the tube reflect light from the other side of the Cherenkov cone onto the MCP's, with the light arriving $\approx$ 785 psec later. The right-hand panel shows the time-of-arrival versus distance along the OTPC axis of hits in the Planacon MCP-PMTs for a single muon event. Two 'tracks' are visible: the track from Cherenkov direct light is earlier than the track made by the light reflected by mirrors on the other side of the tube by 785 psec. The slope is consistent with the muon being fully relativistic. Even though this OTPC proof-of-principle prototype was very short, in a length of 40 cm the measured angular resolution was 16 mrad [20, 21].

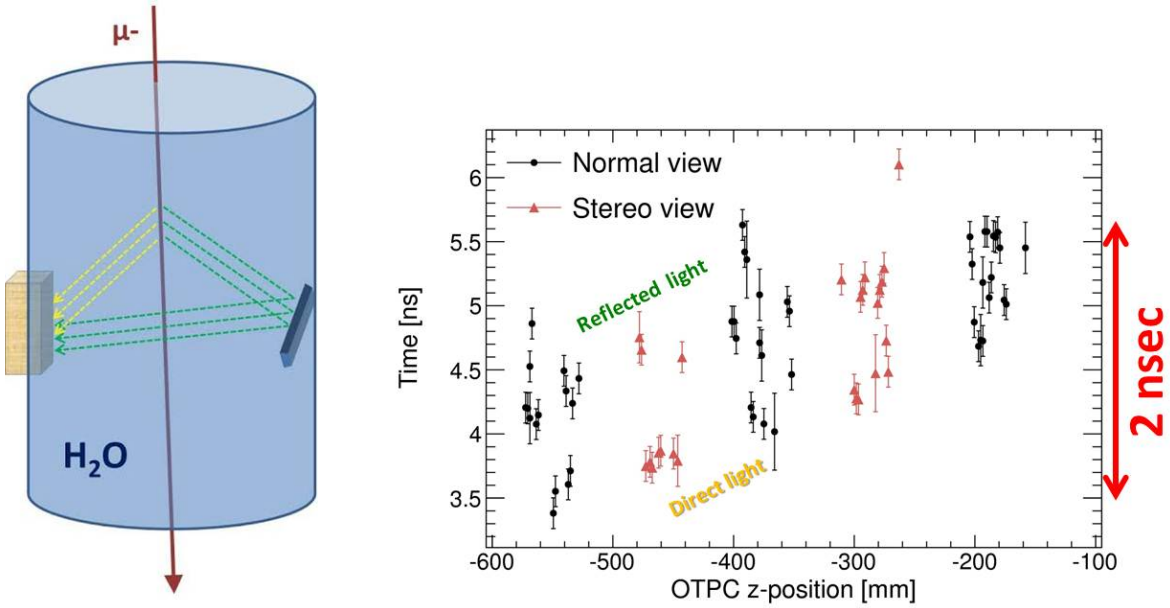

Figure 2: Left:The Optical TPC Concept. The actual OTPC employed 5 Planacons each with 30 measurements, arranged in a stereo configurations [20, 21]. Right: Data from the traversal of a single muon through the OTPC, showing the time of arrival versus distance along the OTPC of hits in the Planacon MCP-PMTs. The reconstructed 'track' from direct light is earlier than that from reflected light by 785 psec.

6.2 Far Detector Optical Considerations

Substantial work has been done on the optical systems for DUNE [23, 24] and would not be affected by this proposal. Also one cannot be specific about a low-coverage optical system or a new detector for Cavern 4 so far in the future. Detailed simulations are essential to determine the dependence on time resolution to the number of photons detected. However some general observations follow.

A low-coverage Precision-4D optical system relies on the detection of Cherenkov light in the optical range by detector modules with time resolutions less than 100 psec. The detectors need to operate at LAr temperature inside the cryostat to avoid penetrations [25]. One attractive possibility is SiPMs, possibly in strips in the gaps between the field cages electrodes [25]. Alternatively, or in addition, a small fraction of the photomultipliers intended for triggering could be left bare without wavelength-shifter.

Mirrored surfaces can be used to amplify cathode coverage and provide stereo information as in the OTPC, including reflections from internal electrical structures [26].

6.3 Machine Learning and More Sophisticated Fitting

Optimizing the photodetector/mirror system coverage and distribution for different event types is a many-parameter problem. It may be a satisfying problem for machine learning.

7 Conclusions

The Stroboscopic method provides an opportunity for the simultaneous measurement of neutrino oscillations using both Far and Near detectors for each of the time-selected spectra in neutrino energy. Liquid Argon-based detectors have an advantage over traditional warm-liquid detectors in that each event is precisely reconstructed in space from the electron TPC data. The reconstructed tracks then can be used to simulate the detected time and position of Cherenkov photons radiated from some or all of the charged particles in the event. The comparison of the 4D-coordinates of simulated photons to those of measured photons depends on one parameter– the time of the event, which can be fitted for.

Chromatic dispersion and other effects can be addressed by limiting the matching to simulated photons in a selected range of wavelengths from the 'truth' information.

The power of the fit will depend on the number of matched hits, which in turn depends on the photodetector coverage. However because one is not reconstructing the event, but instead comparing predicted to measured 4D-hits, a much smaller required coverage is expected. If so, the one-parameter fit method would allow application of the Stroboscopic method to the large Far detectors as well as the Near detector.

8 Acknowledgements

We thank Dave Schmitz for discussion of LAr geometries and constraints.

References

[1] E. Angelico, J. Eisch, A. Elagin, H. J. Frisch, S. Nagaitsev, M. Wetstein. *Energy and Flavor Discrimination Using Precision Time Structure in On-Axis Neutrino Beams.* Phys. Rev. D, 100, 032008. 26 Aug. 2019. arXiv:1904.01611

[2] The Long-Baseline Neutrino Facility (LBNF); https://lbnf.fnal.gov/

[3] *Fermilab-Chicago Psec Timing Meeting*; March 17, 2018; University of Chicago; https://efi.uchicago.edu/content/fermilab-chicago-timing-planning-meeting/.

[4] Precision-4D refers to the '4-dimensional' capability of simultaneously measuring the position and the time of arrival of a particle at a precision comparable to light travel times of several millimeters.

[5] *Workshop on Precision Time-Structure in On-Axis Neutrino Beams*; Fermilab; Nov 2-3, 2019; https://indico.fnal.gov/event/21409/

[6] M. Wetstein, *Physics with Precision Time Structure in On-Axis Neutrino Beams*; Joint Theoretical-Experimental Fermilab Seminar, Nov. 1, 2019

[7] M. J. Minot et. al. *Large area picosecond photodetector (LAPPD^{TM}) offers fast timing for nuclear physics and medical imaging*, Submitted for publication in "Il Nuovo Cimento" Jan., 2020

[8] For example: E. Oberla, the PSEC4A ASIC.
See https://indico.cern.ch/event/697988/contributions/3056053/attachments/1720190/2776726/TWEPP_Porter_poster_163.pdf

[9] The DUNE Collaboration, *Deep Underground Neutrino Experiment (DUNE) Far Detector Interim Design Report; Volume 2*; July, 2018; https://dune.bnl.gov/docs/technical-proposal/far-detector-single-phase-chapter-fdsp-daq.pdf

[10] D. Cussans, *Timing and Synchronization of the DUNE Neutrino Detector*, submitted to Nucl. Instr. Meth A, May, 2019

[11] White Rabbit distribution systems from Seven Solutions, Barcelona, Sp., are being used at Fermilab in the Short Baseline Neutrino Facility and at the Fermilab Test Beam Facility . See https://sevensols.com/index.php/projects/white-rabbit-technology/.

[12] W. F. McGrew et al., *Atomic clock performance enabling geodesy at the centimetre level*; Nature Vol. 564, Dec. 2018.

[13] See, for example, L. Ren et al.; *Mass Production of MCP-PMT for JUNO and Development of 20-inch MCP-PMT with TTS Improved*; Proc. 5th International Workshop New Photon-Detectors (PD18), JPS Conf. Proc. 27, 011014 (2019)

[14] K. Abe et al. (Hyper-Kamiokande Proto-Collaboration); *Hyper-Kamiokande Design Report*; https://arxiv.org/abs/1805.04163

[15] A. Elagin, H. J. Frisch, B. Naranjo, J. Ouellet, L. Winslow, T. Wongjirad; *Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector by Fast Timing*; Nucl. Instr. Meth. Phys. Res. A849, 102 (2017)

[16] A. Li, A. Elagin, S. Fraker, C. Grant, and L. Winslow, *Suppression of Cosmic Muon Spallation Backgrounds in Liquid Scintillator Detectors Using Convolutional Neural Networks*, Nucl. Instr. Meth. Phys. Res. A947, 162604 (2019).

[17] J. Gruszko, B. Naranjo, B. Daniel, A. Elagin, D. Gooding, C. Grant, J. Ouellet and L. Winslow, *Detecting Cherenkov light from 12 MeV electrons in linear alkylbenzene* , JINST 14 (2019) no.02, P02005

[18] We use the convention that $c = 1$ so that time and space can be measured in meters.

[19] P. Adhikari et al. (The DEAP collaboration), *The liquid-argon scintillation pulse shape in DEAP-3600*, arXiv:2001.09855; Jan., 2020

[20] E. Oberla and H.J. Frisch; *Charged particle tracking in a water Cherenkov optical time-projection chamber*, Nucl. Inst. Meth. Phys. Res. A. Volume 814, 1 April 2016,

[21] E. Oberla, *Charged Particle Tracking in a Water Cherenkov Optical Time Projection Chamber*, Ph.D Dissertation, University of Chicago, Aug. 2015

[22] Photonis, Planacon^{TM}; see the Planacon link at http://www.photonis.com/en/product/.

[23] D.L. Adams et al.; *Photon detector system timing performance in the DUNE 35-ton prototype liquid argon time projection chamber* arXiv:1803.06379; June, 2018; submitted to JINST

[24] A. Himmel; *The DUNE Far Detector and ProtoDUNEs*; talk at the 38th International Conference on High Energy Physics, Chicago, IL; Aug. 2016; https://indico.cern.ch/event/432527/

[25] David Schmitz, private communication.

[26] H. J. Frisch; *Drifting Photons on Optical Paths, Mirrors, Sub-mm Resolution in Four Dimensions, and Transverse/Longitudinal Phase Space: Exploiting Psec Time Resolution*. Proceedings of the 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017); May, 2017, Philadelphia, USA; Proceedings in Science, 2018