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

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Abstract

We propose a relatively simple method to measure the event time in liquid Argon (LAr) neutrino detectors that takes advantage of the topological reconstruction of each event *prior* to a 'one-parameter' fit for the time using 'Precision-4D' photodetectors. 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 liquid scintillator detectors.

1 Introduction: Motivation and The Energy-Time Correlation

Fermilab will have the most intense high-energy neutrino beams on Earth, with world-class detectors on-site and at SURF. There will be upgrades in the future to extend the capabilities to higher precision and towards answering new questions. These will require new technologies that by nature have a long lead-time to the required maturity.

1.1 Motivation: The Nature of Neutrino Masses

Questions on the nature of the mass of neutrinos, including whether Dirac or Majorana, and what is the source of the many orders-of-magnitude differences and the dependence on family, are central to Fermilab's intellectual landscape. The questions surrounding the baryon-antibaryon asymmetry that we enjoy and CP violation may have answers in the neutrino sector.

1.2 The Stroboscopic Method

The Fermilab-Chicago Timing Planning Meeting workshop [1] was held in 2018 to discuss what currently inaccessible physics one could do with 'precision-4D' measurements [2]. The discussion led to a proposal to rebunch the Main Injector beam at 531 MHz to produce shorter proton bunches [3]. 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, Fermilab and Chicago held a second meeting at Fermilab, the Workshop on Precision Time Structure in On-Axis Neutrino Beams [4], to vet details with an expert audience.

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. 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 bins have a much softer distribution in neutrino energy than the earlier arrival bins.

The beauty of this is in the correlation of neutrino energy with a measured parameter, the time of arrival relative to the RF, that is not directly related to the measured neutrino energy. Each energy 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.

The Stroboscopic proposal 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.

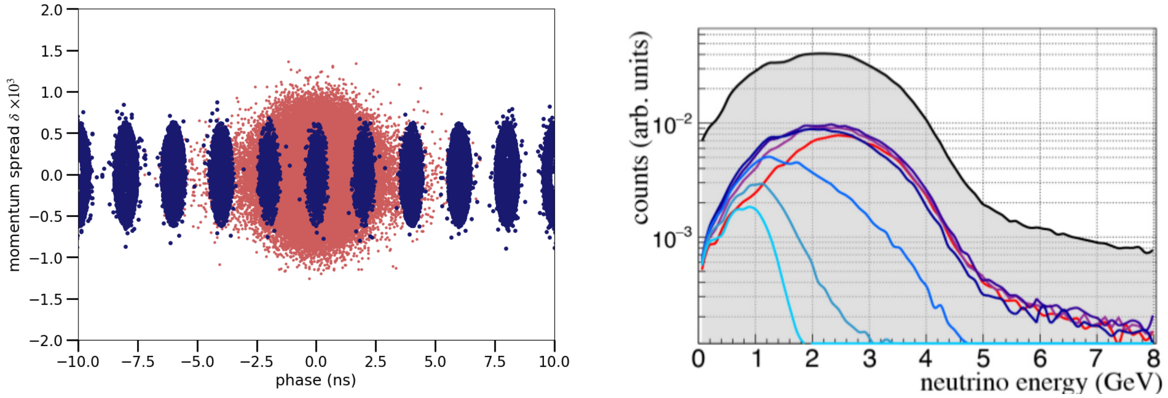

Figure 1: Left: the momentum spread for one bunch of the current 53 MHz Main Injector beam versus the phase in nanoseconds (Red), and for the beam rebunched on the 10th harmonic (Blue). Right: the neutrino momentum spectra in 200 psec bins of time of arrival relative to the proton bunch assuming a 100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

1.3 Precision-4D Large-Area Photodetectors

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 a tightly constrained 3-dimensional imaging given enough detected light.

In 2009 the LAPPD Collaboration was formed to develop affordable large-area fast timing photodetectors with excellent resolution in 4-dimensions [5]. Incom, Inc is now producing commercially-available modules at the rate of up to 6/month [6]. There now exists a robust sealing technique [7] and a proposed method for large-scale batch production [8, 9]. The system proposed below for the DUNE far detector fits easily in the production schedule of such a facility in less than one year.

1.4 The Challenge of Precision-4D Coverage in Very Large Detector

The reconstruction of the event time in large warm-liquid detectors such as JUNO [10] 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 from scintillation light [11, 12, 13]. For a detector the size of the DUNE Far detector, the photodetector cost and scope of the detector upgrades would be enormous. 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 has been considered a non-starter [4].

2 The Post-Reconstruction One-parameter Fit

However, the situation in LAr is different from that in conventional large liquid scintillator detectors. Here we propose to use the LAr event reconstruction from the drifted charge as input to a fast simulation that would generate Cherenkov light from the reconstructed tracks. The photons would be mapped onto the simulated detector surfaces as a function of the event time. 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 event time then yields a best-fit time of event and uncertainty.

2.1 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 [14], i.e. on the order of 10 psec light travel time [15]. This is small compared to the Stroboscopic time binning [16]. 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 [14] after corrections.

2.2 Fitting for the Event Time

2.2.1 The Precision Time Reference

Time at the Near and Far detector locations [17] and bunch-by-bunch at the production target would be recorded relative to a master clock distributed via a system such as White Rabbit [18, 19]. Synchronization among these three locations at the required level is within the capabilities of current technology [20]. The requirements for clock distribution within to the photodetectors within each of the Near and Far detectors are within the capabilities of the current system at the TestBeam [19].

2.2.2 Recording the time and position of Cherenkov photons in the precision-4D photodetector system

A possible electronics architecture for the precision-4D photodetector consists of a multi-buffer waveform sampling front end [21] with a buffer length long-enough to accommodate the DUNE trigger latency [22]. The measured hit times and clock and bunch reference data forms a data stream to be merged with the reconstructed LAr data.

2.2.3 Generating the time and position of Cherenkov photons from the LAr data after 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 recorded. Additional truth information such as photon wave-length, polarization, and scattering history is also recorded.

2.2.4 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 Chi-squared 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.

2.2.5 Measuring, correcting for, and exploiting chromatic dispersion

The list of predicted hits 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 photons in a limited wavelength range to minimize dispersion. After the fit, other, un-matched fits, can be fit as a function of wavelength, adding chromaticity to the set of measurements. Similar information on photon scattering and absorption, for example, can be extracted from the data.

3 Photodetector Coverage as a Parameter

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 optimized. A given ‘tiling’ of the detector surfaces with photodetectors yields the number of matched hits versus event time. The match rate versus coverage informs the scope of the required coverage.

3.1 The Use of Mirrors

Precision-4D detectors allow mirrors to multiply photocathode coverage by using the drift time of photons to constrain the distance to the source. In Section 3.2 we describe the performance of the Oberla's OTPC prototype in the Fermilab Test Beam. Section 3.3 briefly describes some general considerations of a Precision-4D implementation.

3.2 The Optical Time Projection Chamber

Figure 2 shows the small Optical TPC, which was tested in the Fermilab MCenter test beam [23, 24]. The left-hand panel shows the concept. A plastic tube filled with water provides Cherenkov radiation for particles traveling down the tube; five Planacon [25] 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 [23, 24].

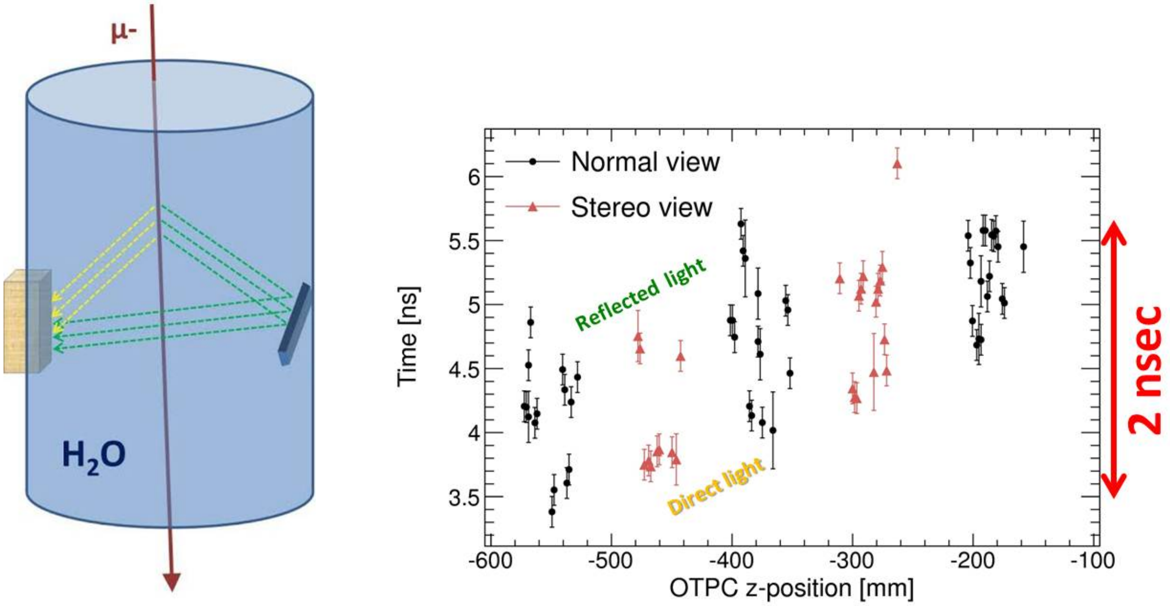

Figure 2: Left:The Optical TPC Concept. The actual OTPC employed 5 Planacons each with 30 measurements, arranged in a stereo configurations. Right: Data from the traversal of a single muon through the OTPC, showing the time of arrival versus distance along the OTPC of hits in the Planacon MCP-PMTs. The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

3.3 Far Detector Optical Considerations

Substantial expert work has been done on the optical systems for DUNE [26, 27]. It is hard to be specific about a new 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 [28]. One attractive possibility is SiPMs, possibly in strips in the gaps between the field cages electrodes [28].

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

4 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.

5 Conclusions

Upgrades to the current Fermilab program in neutrino physics will be necessary to extend the current projected capabilities to higher precision and towards answering new questions. These will require new technologies that by nature have a long lead-time to the required maturity. It is not too early to do the basic ground work for an estimate of the physics gain and a conceptual design.

The Stroboscope method provides an opportunity for the simultaneous measurement of neutrino oscillations using both Far and Near detectors with differing time-selected neutrino energy spectra. Liquid Argon-based detectors have an immense advantage over traditional liquid scintillator-based detectors in that each event is reconstructed from the electron TPC. The reconstructed event then can be used to predict the time and position of Cherenkov photons radiated from some or all of the charged particles in the event, along with associated uncertainties. The comparison of this list versus the measured hit list depends on one parameter- the time of the event, which can be fitted.

The geometry of the Optical TPC [23] of Precision-4D detectors on one surface with mirrors on opposing surfaces may be natural to the LAr geometry of a central cathode at negative HV and an anode surface at ground.

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 hits, a much smaller required coverage is likely. If so, the one-parameter fit method would allow application of the Stroboscopic method to both the Near and Far detectors.

6 Acknowledgements

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

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