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Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber

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Abstract

MicroBooNE is a liquid argon time projection chamber (LArTPC) in the Fermilab Booster Neutrino Beamline. In Summer of 2015 the detector was filled with liquid argon and commissioned. In this note we present the temperature and fill-level dependence of the noise measured on the wire signals. We observe the expected decrease of noise for the CMOS ASIC and the increase in wire noise due to the change in dielectric when submerged in liquid argon.

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1 Introduction

1.1 The μBooNE Experiment

μBooNE is a liquid argon time projection chamber (LArTPC) in the Fermilab Booster Neutrino Beamline. μBooNE's TPC is a rectangular liquid argon volume enclosed by a field cage with dimensions 2.3 m vertical 2.3 x 2.5 m horizontal x 10.4 m long. The cathode (anode) defines the beam-left (right) side of the active volume. The anode is composed of three layers of wires with plane-to-plane spacing of 3 mm, and each plane has 3 mm wire pitch. Two wire planes are oriented at 60 degrees relative to vertical and one plane vertically oriented wires. μBooNE uses cryogenic low-noise front-end electronics submersed in the liquid to obtain optimum detector performance. The front-end ASIC and associated circuits are implemented on a cold mother board, which is attached to wire carrier boards on the TPC directly. Cold cables are used to transmit output signals from cold mother boards to warm interface electronics installed on the top of signal feed-through flanges.

1.2 Noise Behavior in the TPC

The weeks in which the μBooNE cryostat was cooled down and filled with LAr presented a unique opportunity to study the noise dependence on both the cryostat temperature as well as the LAr fill level within the TPC. In this document we present a study of such measurements.

Temperature Dependence of Noise: Noise measured on TPC wires is expected to vary with the temperature of the cold electronics. The temperature-dependence of noise in the TPC is dominated by the characteristics of the CMOS analog front-end ASIC. A detailed description of this dependence is beyond the scope of this work. More information on the CMOS analog front-end ASIC used in μBooNE can be found in Ref. [1].

LAr Submersion Level Dependence of Noise: Noise measured on wires in the μBooNE TPC is expected to depend on the material in which they are immersed. Materials with different dielectric constants will change the effective capacitance of the wires, thus changing the Equivalent Noise Charge (ENC) recorded. Liquid Argon (LAr) has a larger dielectric with respect to gaseous argon (1.504 vs. 1.001), and this in turn will affect the noise levels recorded. We expect the noise levels to vary as the depth to which wires are submerged in LAr changes. From Eq. 1, 2, and 3 one sees that this dependence is expected to be linear.

$$\mathrm{ENC} \propto C_{\mathrm{tot}} \tag{1}$$
$$C_{\mathrm{tot}} = C_{\mathrm{wire}} + C_{\mathrm{other}} \tag{2}$$
$$C_{\mathrm{wire}} \propto \epsilon_{\mathrm{Ar}} \tag{3}$$

Where C_{tot} is the capacitance of the system, C_{wire} is the capacitance of the wire, and ϵ_{Ar} is the dielectric of liquid or gaseous argon.

In this document, ENC measurements are reported in units of number of electrons (e^-). To give a sense of scale, we provide estimates for the expected magnitude of the signal in the μBooNE TPC. The ionization energy of Ar is 23.6 eV, meaning $\approx 4.2E4$ e^-/MeV of deposited energy. A Minimally Ionizing Particle (MIP) traversing the TPC parallel to the wire-plane is expected to deposit $\approx 2.5E4$ e^- on a single wire (2 MeV/cm MIP with 0.3 cm wire-spacing). This quantity can be used to estimate our expected signal-to-noise ratio.

In Sec. 2 we describe what data-set was used for this analysis. Sec. 3 describes how noise, temperature and LAr fill level measurements were obtained. Sec. 4 describes the noise level dependence on temperature inside the cryostat. Sec. 5 shows the temperature dependence on the level of LAr in the TPC. Finally, Sec. 6 briefly summarizes this work.

2 Data Selection

For this study the data-set used contains runs taken in the months of May, June, and July 2015. These are runs taken in the early stages of the μBooNE detector commissioning phase. During this period the drift high-voltage, wire-bias, and PMT systems were all turned off. The data taken needed to match the following criteria in order to be used:

- the ASIC gain setting used was set to 14 mV/fC (second highest value).
- the shaping time was set to 1 μs.
- only noise-runs were used (all data taken when pulsing the calibration capacitors was excluded).
- only collection-plane wires were used for this study. This allowed for removal of any noise dependency on the wire-length.

An additional cut on the noise level measured on collection-plane wires was applied. This was done to remove low-noise and high-noise wires that would skew our results. The channels removed are ones for which noise is not dominated by the regular noise sources in the detector and cold electronics. Because we wish to study the temperature and LAr-level dependence of these noise sources, excluding these channels from our sample is reasonable.

2.1 RMS Noise Based Cut

To remove low and high-noise channels from the data sample used in this study a cut was applied to the RMS noise measured on all channels. An upper-bound cut of 5 ADC RMS was used to remove particularly noisy channels. Except for a small set of runs, this cut always removed only the two known noisy collection-plane channels (crate 8, slot 17, channel 47/48). Similarly, a lower-bound cut was applied. The cut value was of order 1 ADC RMS, but was allowed to vary to account for the varying noise level due to the changing cryostat temperature. This cut value was chosen such that it would separate two clearly distinct distributions visible in the data-set: channels with nominal noise levels and channels with a lower than expected RMS noise. These low-noise channels have noise levels consistent with a mis-configured or non-configured ASIC. On average, 93% of all collection-plane channels passed these cuts. A more detailed discussions of the impact of these cuts is described in Appendix **??**

3 Analysis Methodology

For each run taken satisfying the requirements in Sec. 2 a measurement of the noise on the collection-plane wires was performed. For channels passing the RMS cuts described in Sec. 2.1 the average and standard deviation of the distribution of RMS values were taken as a measure of the noise in the TPC. An example of the distribution of RMS levels surviving the cuts described for a given run can be seen in Fig. 1. The spread in RMS levels on the different channels is due to the channel-to-channel variation in electronics gain.

For each channel, the RMS was calculated by finding the quadratic mean of baseline-subtracted ADC counts for all ticks in a 9,600 0.5μs time-ticks readout window. Eqns. 4 and 5 show how this quantity was calculated:

$$\text{Baseline}_{\text{ch}} = \frac{\sum_{i=0}^{N} \text{ADC}_{\text{ch},i}}{N} \tag{4}$$

$$\text{RMS}_{\text{ch}}{}^2 = \frac{\sum_{i=0}^{N} (\text{ADC}_{\text{ch},i} - \text{Baseline}_{\text{ch}})}{N} \tag{5}$$

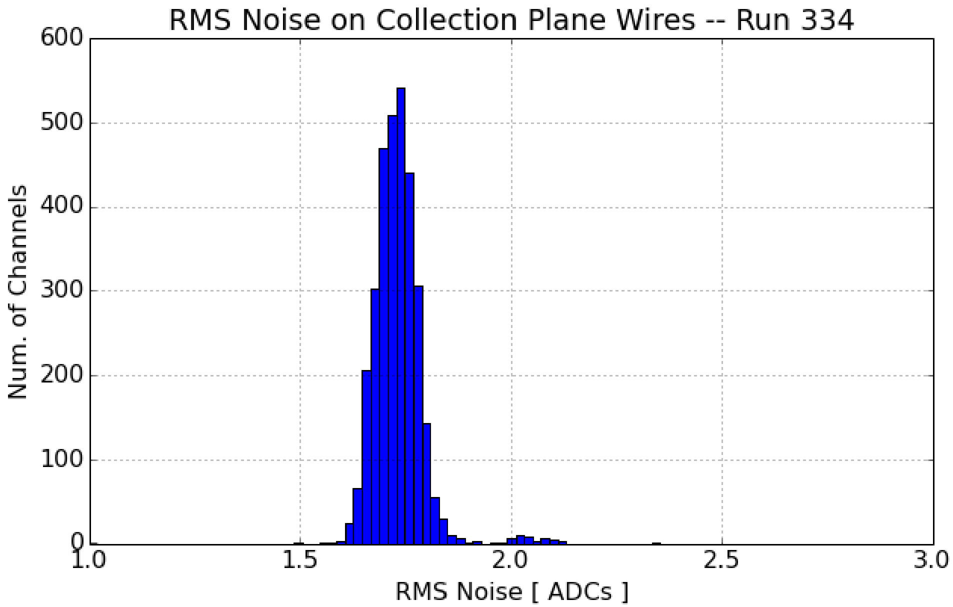

Figure 1: Distribution of RMS noise on all collection plane wires surviving the cuts described in Sec. 2 for run 334

For each run, a time associated with that run was found using the DAQ logs. The time used is the time at which the run was initiated. In this study we used data from the first couple of events from each run, making this a good measurement of the time at which the run was taken (an error of order 1 minute is estimated).

Cryostat temperature and LAr fill levels were acquired using the slow-monitoring control system. Noise measurements taken at each run were then associated with a specific temperature or LAr fill level by finding the value logged closest in time to the run's time. Temperature and LAr-fill levels were logged approximately every second.

Finally, a constant conversion factor was used to go from ADC to ENC (Equivalent Noise Charge). The conversion applied is shown in Eq. 6.

$$\mathrm{RMS[ENC]} = \frac{\mathrm{RMS[ADC]}}{1.6 \times 10^{-4}\ [\mathrm{fC/e^-}] \times 14\ [\mathrm{mV/fC}] \times 1.935\ [\mathrm{ADC/mV}]} \tag{6}$$

The factor of 1.935 [ADC/mV] was measured as the average gain on collection-plane channels from data taken in the summer of 2014 while performing readout tests.

3.1 Error Analysis

Throughout most of this document, for each run analyzed we plot an error bar associated to the standard deviation of RMS values measured on collection plane channels surviving the aforementioned cuts. These error bars are not meant to indicate the uncertainty on the measured data-point ($\sigma/\sqrt{N}$) but rather the spread in noise values due to channel-to-channel gain variations. We hope this provides a useful comparison between the intrinsic variations in noise one can expect within the detector at fixed conditions, versus the variations due to temperature or LAr-level changes that we study.

4 Temperature Dependence on Noise

4.1 Temperature Measurements

To determine the temperature in the cryostat at any given time, we relied on the temperature reading from two different sensors within the TPC: sensors TE192 and TE196, which were located at the top and bottom of the TPC frame, respectively. The average of these two temperatures was used for this study. Fig. 2 shows how the temperature in the TPC changed over the course of the cool-down.

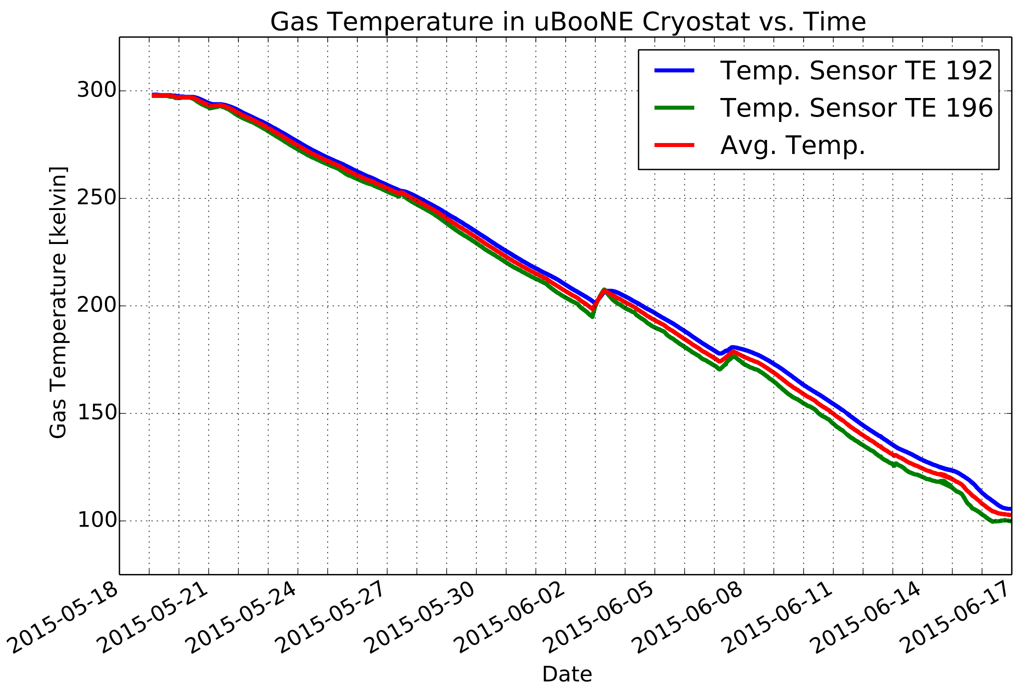

Figure 2: Temperature in the μBooNE cryostat over the course of the cool-down. Sensors TE192 and TE196 were located on the top and bottom of the TPC frame, respectively. In red we show the average of the two, used in this analysis.

4.2 Noise vs. Time

Noise measurements as a function of time can be seen in Fig. 3. Each data point represents a noise measurement for a given run. The time shown is the time at which the run was taken. Data points and error bars correspond to the average and standard deviation, respectively, of the distribution of RMS noise measured on all collection plane wires that pass the cuts described in Sec. 3 for a specific run.

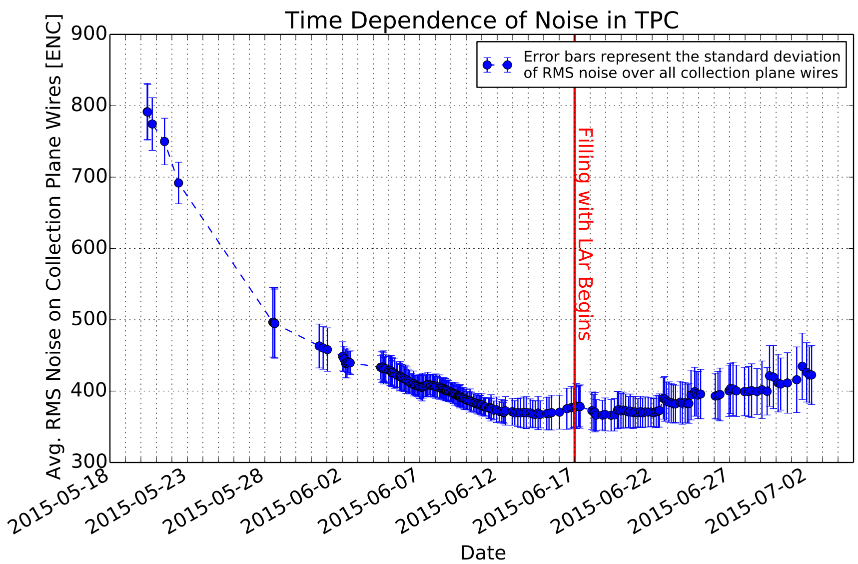

Figure 3: Noise measured on collection plane wires as a function of time. Each data point corresponds to the measured noise level for a given run. The times shown are the times of each run. Data points and error bars are the average and standard deviation, respectively, of the distribution of RMS values measured on collection-plane wires. The vertical red line marks the date on which the LAr filling began.

4.3 Noise vs. Temperature

By relating the noise and temperature measured at a given time we can produce a plot showing the correlation between noise in the TPC and cryostat temperature. This can be seen in Fig. 4

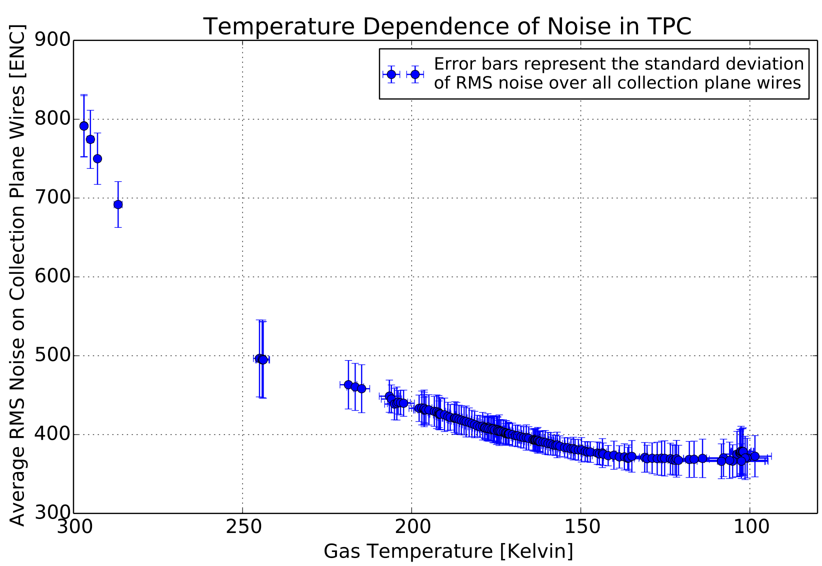

Figure 4: Noise on collection-plane wires vs. gaseous argon temperature inside the μBooNE cryostat. Noise measurements are shown in equivalent noise charge. Each data point shows the average RMS-noise value on collection-plane wires for each run. Error bars correspond to the spread in RMS-noise values due to channel-to-channel variations. Only channels passing the cuts described in Sec. 2 were used.

5 LAr Fill Dependence of Noise

5.1 LAr Level Measurements

The level of liquid argon submerging the TPC was measured using the LAr fill level recorded on the slow controls. Because the noise on the wires will be affected by the portion of wires submerged in liquid, we measure the LAr level from the bottom of the TPC frame. To do this we subtract 74.5 cm from the LAr level measurement reported on the slow-control monitor. This corresponds to the distance between the bottom of the cryostat and the bottom of the TPC. Fig. 5 shows the level of LAr in the μBooNE cryostat (as measured from the bottom of the cryostat) over the weeks during which the filling process occurred. We shade in grey the times at which the LAr level fell above the bottom, but below the top of the TPC frame.

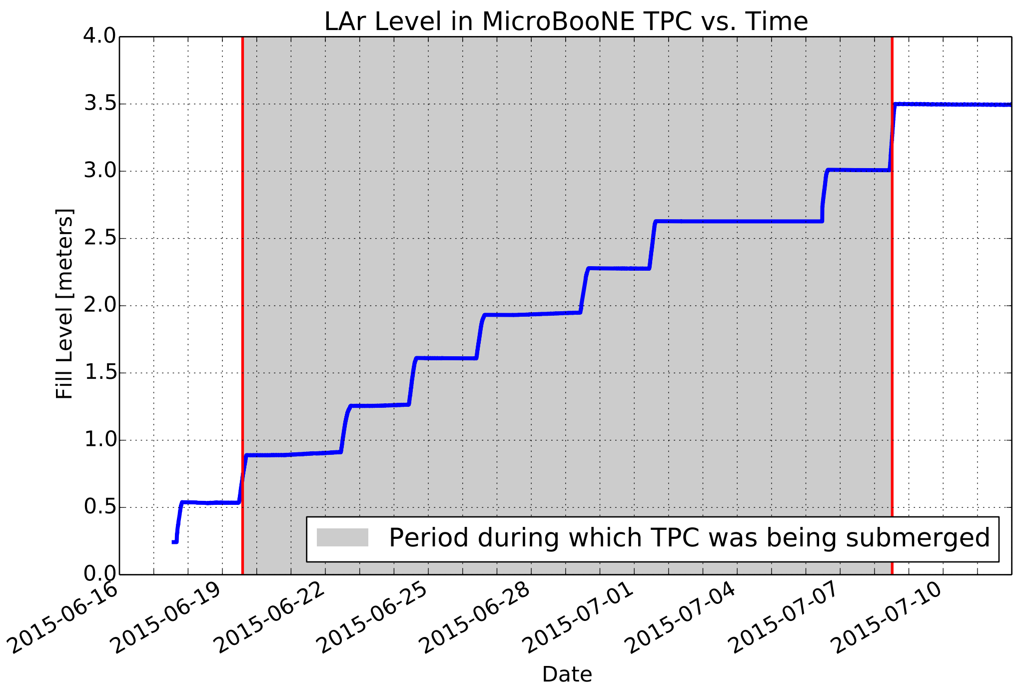

Figure 5: LAr fill level over the several weeks during which the filling process occurred. The fill level is measured relative to the bottom of the cryostat in meters. The fill level is calculated from a gas-pressure measurement in the TPC. The shaded grey area marks the tine in which the LAr level fell between the bottom and top of the TPC frame. Each step in this plot marks the approximate time of a fill.

5.2 Noise vs. Time

We next show the noise measured on collection plane wires for the time period in which the fill was occurring. The data-points on this plot were calculated using the same method followed in Sec. 4. Fig. 6 shows in blue the noise measurements over time. Red vertical lines mark the approximate time of each fill. A fill is defined as the introduction into the μBooNE cryostat of a single truck-load of high-purity LAr delivered by the vendor. Fills generally occurred every other day on weekdays. Each fill took several hours to complete.

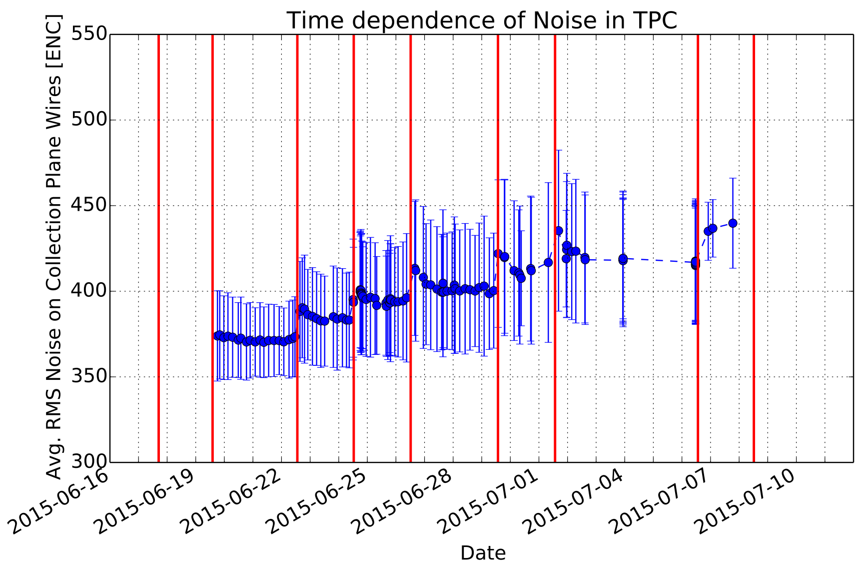

Figure 6: Noise on collection-plane wires at different times during the filling process. Vertical lines represent the approximate time of each fill. Data-points represent the mean noise value measured on collection-plane wires passing the cuts in Sec. 2. Error-bars show the standard-deviation of the noise on these channels and give a sense of channel-to-channel gain variations.

Fig. 6 shows a clear upwards trend: with successive fills the noise level in the TPC increases. One can however clearly notice additional features in this plot. After each fill, noise levels seem to rise quickly, and subsequently slowly decrease to a stable value. This could be due to wire or liquid motion within the cryostat during the fill process. In addition, the behavior after the last fill seems qualitatively different from the others. The noise levels increase by more than they had previously, and they are very stable in time. These differences can be due to the fact that by the last fill, the entire TPC was submerged in LAr, and with the last fill all the cold electronics (motherboards, pre-amplifiers) became submerged as well.

To focus on the LAr level dependence of noise, we applied two further cuts to the list of runs used in this analysis. Runs which matched the following criteria were removed:

- Runs taken fewer than 3 hours before a fill or fewer than 24 hours after one. The 24 hour requirement was set to allow the LAr and noise levels in the TPC to stabilize. Runs taken 3 hours before a fill were also removed: this is because each fill actually extended several hours, and we wanted to make sure we were not using data taken during a fill.
- Runs taken when the fill level, with respect to the bottom of the TPC, was below 0 cm or above 235 cm, were removed. This was done so that we could remove runs in which the LAr-level was below or above the TPC frame.

After these further cuts, the set of data-points used in the study was reduced to that shown in Fig. 7

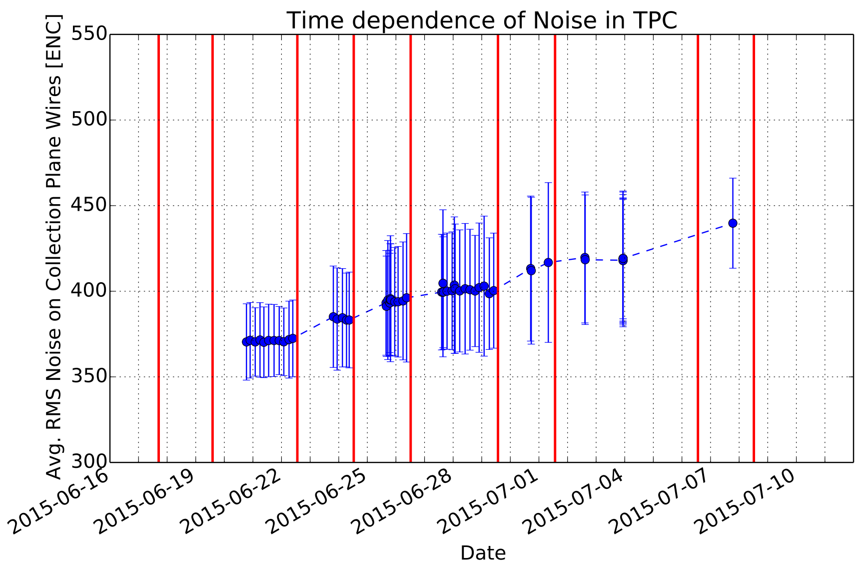

Figure 7: Noise on collection-plane wires at different times during the filling process. Vertical lines represent the approximate time of each fill. Runs taken 3 hours before or 24 hours after a fill were removed. Additionally, runs taken when the LAr level was below or above the top of the TPC were also removed.

5.3 Noise vs. LAr Fill Level

Finally, we are ready to study the dependence of noise in the TPC on the submersion level of wires. This correlation is shown in Fig. 8. In this figure, a data-point for each fill level is plotted. The average fill level and noise level was calculated from the data-points measured after each fill. The same relative error was applied to all points. The error was calculated by finding the largest spread in the distribution of the means from a set of runs taken at a specific fill level. The largest spread was found for runs taken after the fill that occurred on June 27th. This error calculation is meant to provide an estimate of the systematic fluctuations in noise not accounted for by statistical uncertainties.

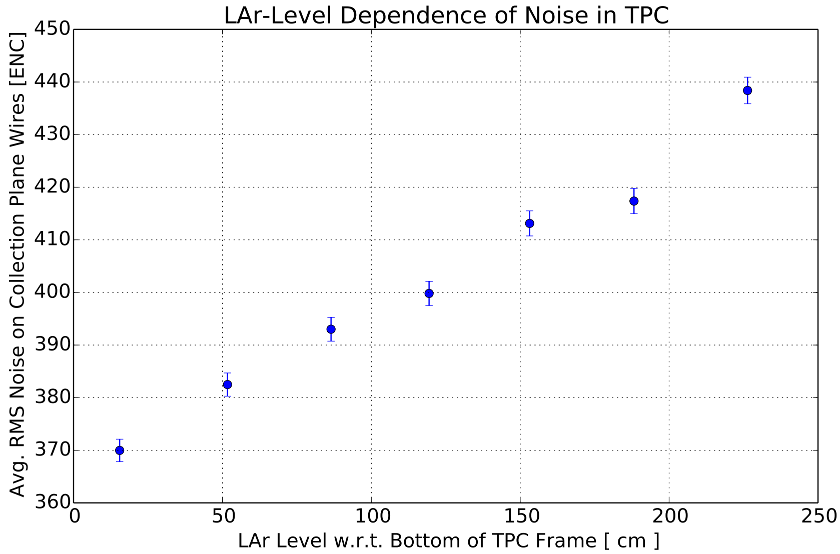

Figure 8: Noise on collection plane wires vs. LAr submersion level of the μBooNE Time Projection Chamber. In this figure, a data-point for each fill level is plotted. The average fill level and noise level was calculated from the data-points measured after each fill. The same relative error was applied to all points. The error was calculated by finding the largest spread in the distribution of the means from a set of runs taken at a specific fill level. The largest spread was found for runs taken after the fill that occurred on June 27th.

6 Conclusions

In this document we have studied the temperature and LAr-fill level dependence of noise in the μBooNE TPC. We expected to see a strong temperature-dependence of noise values in the TPC signal wires due to the CMOS ASIC's design (See Ref. [1]). Likewise, the noise measured on the wires was expected to increase as gaseous argon was replaced with liquid argon during the filling process, as the dielectric constant of the material surrounding the wires increased. These results follow the behavior expected. Fig. 4 and 8 show both these trends. Fig. 4 shows a very strong dependence of noise on the surrounding gas' temperature: the decrease in noise proceeds rapidly at higher temperatures and begins to saturate once we reach ≈ 100 K. Likewise, Fig. 8 shows the linear relation between noise and fill level which we expected due to the changing effective dielectric constant in the medium.

We hope these measurements can serve as a benchmark for future LAr-TPC detectors. While in this document we have mostly focused on providing a qualitative understanding of the dependencies of noise on various factors, we hope to follow up this document with a more quantitative study.

References

[1] Gianluigi De Geronimo et. al. *Front-End ASIC for a Liquid Argon TPC*
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 58, NO. 3 pp. 1376-1385, JUNE 2011