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First neutrino interactions observed with the MicroBooNE Liquid-Argon TPC detector

The MicroBooNE Collaboration

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Abstract

The MicroBooNE liquid-argon TPC detector started to take its first neutrino data from the Booster Neutrino Beam at the Fermi National Accelerator Laboratory on October 17, 2015. We have performed fully-automated 3D reconstruction on these first data events using algorithms we have developed for the LArSoft software package, and we have developed a filter to distinguish neutrino interaction candidate events from the large number of events that contain activity originating mostly from cosmic rays. This is the first-time events from a large liquid argon TPC operating on/near the surface have been automatically reconstructed and selected for analysis. We describe the reconstruction and automated filtering procedure, and show displays of some of the first neutrino interactions observed with the detector using 1.86×10^{18} protons on target.

1 Introduction

The MicroBooNE detector is a liquid argon time projection chamber (LArTPC) at the Fermi National Accelerator Laboratory, that is designed to study short baseline oscillations and neutrino-argon interactions. It is located 470 m downstream from the proton target in the Booster Neutrino Beam (BNB). The detector consists of a cathode plane being operated at -70 kV, and more than 8000 sense-wires in three anode planes reading out the signal of ionization electrons produced in the LAr volume and drifting towards the anode. The first two wire planes read out induction signals from passing electrons, while the last plane sees signals from electrons collecting on the wires. Behind the anode wire planes, a light collection system consisting of 32 8-inch photo-multiplier tubes measures the scintillation light produced by interactions in the detector [1].

Over the past year, the MicroBooNE detector has been commissioned and prepared for the start of its physics run. On August 6, 2015, while the neutrino beams were in a maintenance shutdown, first tracks of cosmic ray induced particles have been observed in the detector [2]. On October 17th 2015 the BNB delivered first beam for physics data-taking after an accelerator maintenance shutdown, and MicroBooNE started recording its first neutrino events.

Since the MicroBooNE detector is located near the surface, there is a steady flux of cosmic-ray-induced particles recorded by the detector at all times. MicroBooNE's data acquisition system receives trigger signals from the BNB, and upon each trigger the detector reads out a 4.8 ms long "readout" window around the trigger time. Within each 4.8 ms readout window, there are on the order of 7 to 12 cosmic-ray-induced charged-particle tracks or electromagnetic showers. We expect the chance of such a 4.8 ms window containing a neutrino interaction from the BNB is only about 1 in about 660, with the BNB operating at its normal intensity of 4×10^{12} protons per pulse.

This large number of events and the low signal-to-background ratio require an automated selection of neutrino candidate events. In Section 2, we describe this selection procedure, which is based on timing information from scintillation light in matched to the beam spill time, and topological information based on 3D-event reconstruction. In Section 3, we show event displays of some of the the first neutrino interaction candidate events.

2 Automated neutrino event selection

Events in MicroBooNE are fully reconstructed within the LArSoft software framework[3], which is a general simulation, reconstruction, and analysis software package for liquid-argon TPC detectors.

The automated selection of neutrino candidate events is based on two different elements. The first is the determination of the time coincidence of activity in the detector with the pulsed neutrino beam, based on detection of prompt scintillation light produced by particle interactions in liquid argon. The second is the identification of event topologies specific to neutrino interactions, based on drifted ionization charge signals on the TPC wires. We create two independent event filters based on the reconstruction of the optical detector system, which accomplishes the first element, and the TPC reconstruction, which accomplishes the second. The combined application of these filters serves two important tasks: it brings the overall number of passing events to a total that it is feasible to run through the complete reconstruction chain; and, it achieves a high purity of contained neutrino interaction events. The two selections are described in brief detail below.

2.1 Beam timing and optical detector reconstruction

The duration of the BNB spill is 1.6 μs, which is a short fraction of the 2.3 ms it takes for electrons to drift from the cathode to anode wires. During the drift time the detector sees additional activity due to incoming cosmic rays, which may produce ionization charge that is collected by the detector in the 2.3-ms drift window. Therefore, we need to determine the exact beam spill period in our detector signals, and we need a way of determining if any interaction occurred during that beam spill period. Fortunately, charged particle interactions in LAr produce, alongside ionization electrons, scintillation light. A component of this scintillation light is prompt (within nanoseconds of the ionization), and is detected by our optical system. We therefore reject any event without optical detector activity during the beam spill window as not containing a beam-induced neutrino interaction.

The optical reconstruction algorithm starts by identifying pulses on each of the photo-multiplier tubes. These “optical hits” are characterized by their amplitude, width, time relative to the trigger, and the PMT on which they occurred. Hits that occur coincident in time across the detector are grouped into a “flash”. Each flash is also characterized by an amplitude, width, and time relative to the trigger, based on weighted sums of its composite optical hits. Each flash is a reconstructed detection of prompt scintillation light produced by charged particles in the volume of the detector.

Figure 1 shows the time distribution of flashes with amplitude greater than 50 photo-electrons (N_{PE}) over all PMTs. The trigger is issued at time 0, which opens the beam window and starts unbiased PMT readout. The expected background rate was measured to 1.38% using high statistics beam-off data. The bins in-time with the beam spill show a clear excess of observed flashes above the flat rate caused by cosmic-ray-induced backgrounds. The measurement of the time at which we observe this excess is used to calibrate the offset between the beam spill time and the triggered start of the readout window. This corresponds to the advance arrival of the proton extraction into the beamline. Based on these early studies of reconstructed flashes, we have bounded the location of the 1.6μs-long beam-spill period to between 3 μs and 5 μs after the triggered start of the readout window.

In further studies, we require that events have a reconstructed flash with the following properties:

- have $N_{\mathrm{PE}} > 50$, to reduce noise and other background rates; and,
- have a reconstructed time between 3 and 5 μs after the event trigger is received.

Based on an investigation of rates using data with no neutrino beam (only cosmic-ray muons), we determine that the probability of an event having a cosmic-ray-induced flash with $N_{\mathrm{PE}} > 50$ within the beam spill is 1%. Therefore, this requirement reduces the rate of background events by about two orders of magnitude while retaining more than 80% of neutrino interactions, based on studies from Monte Carlo simulations.

2.2 Event topology and TPC reconstruction

Even after the reduction in the number of cosmic-ray events that pass the optical reconstruction selection (described in 2.1), there are still a significant number of events that do not contain a neutrino interaction. Additionally, even in those events that contain a neutrino interaction, there is still cosmic-ray-induced activity, and the neutrino interactions must be distinguished from that. We reconstruct the ionization charge in the TPC and apply cuts on the reconstructed event topologies to identify likely neutrino interactions.

The TPC reconstruction chain is as follows. Data from each wire is passed through a noise filter, signal deconvolution, and calibration to translate raw signal pulses to nearly uniform, unipolar signal pulses on each of the wires. TPC “hits” are identified as Gaussian-like signals above the baseline readout waveforms. Hits in each plane of wires are processed by clustering algorithms which identify hits likely originating from the same particle. 3D pattern-recognition and tracking algorithms then match these hits and clusters across the three wire planes in the TPC—based on reconstructed drift times of the hits, and whether hits are on wires that intersect—to identify charged-particle trajectories (“tracks”) and interaction vertices.

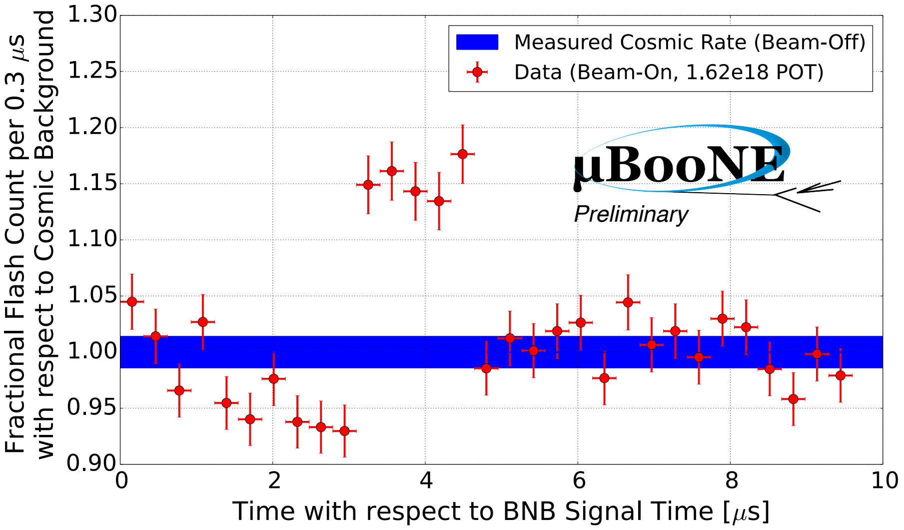

Figure 1: The ratio to a flat cosmogenic background (measured in a high-statistics beam-off sample), of the number of flashes per 0.3 μs as a function of time with respect to trigger time. Data from the first week, totaling 1.62×10^{18} protons on target (POT) were collected and PMT flashes below 50 photoelectrons were discarded. The remainder of PMT flashes were included in this plot. There is a clear excess due to beam events between 3 and 5 μs after the beam trigger. This allows the effective rejection of all events which do not contain flashes in this window, reducing the cosmogenic event rate by a factor of over 100.

To identify event topologies common to neutrino interactions, we have constructed 2D- and 3D-reconstruction selection requirements that identify interactions with at least two charged-particle tracks emanating from the same interaction vertex, within a few cm. The 2D and 3D selection are run independently. The requirements for each selection are explained in the lists below.

For the 2D selection, we analyze reconstructed clusters on the third (collection) plane of wires, and require the following:

- All clusters must pass a cosmic-ray-tagging algorithm, which rejects clusters that are clearly out-of-time with the trigger by identifying any cluster containing hits that are not within the 2.3 ms drift window.
- Of those clusters that pass the cosmic-ray-tagging algorithm, there must be at least two clusters whose distance between start points is less than 3 cm.
- These 2D clusters must contain a minimum of 10 hits and have a minimum length of more than 30 wires in the Y-plane or more than 30 time ticks.
- Long clusters (those with a length of greater than 200 wires, which is a projected length along the direction of the beam of > 60 cm) must be forward boosted with an angle relative to the beam direction of less than 30° in the collection-plane projection. This does not correspond to a physical angle, since the second coordinate is measured in time ticks instead of distance.
- The longer of both clusters, which is likely a muon track, is required to be forward boosted (angle relative to beam direction of less than 30° in the collection-plane projection) and have a length greater than 100 wires.
- If the longer of both clusters has a length of less than 500 wires, then the shorter cluster must have a higher starting charge deposited.
- The opening angle between both clusters is required to be between 11° and 90°. This helps to avoid fake signals by radiation emitted along a cosmic ray muon track or by aligned clusters originating from the same track that has been broken up in reconstruction.
- The charge deposition at the reconstructed end of a cluster is greater than that at the beginning of the cluster. This helps reject events where a muon decays into an electron, which can mimic an interaction topology except that they contain tracks that have their highest energy-deposition near the interaction vertex rather than away from it.

For the 3D selection, we analyze reconstructed tracks and vertices that utilize information from all three wire planes, and require the following:

- Two 3D tracks with their start points within less than 5 cm from each other and from a common reconstructed vertex.
- Both tracks must be fully contained in the detector volume (their start- and end-points must be more than 10 cm from all TPC boundaries), and therefore must not be vetoed by our cosmic-ray tagging algorithms which identify tracks that pass through detector boundaries or that are clearly out-of-time with the trigger.

MicroBooNE Preliminary

First ν identification 1.86E18 POT, BNB

Number of events	Automated event selection Optical + 3D-based	Automated event selection Optical + 2D-based
Non-beam background (expected)	4.6 ± 2.6	385 ± 24
Total observed	18	463

Table 1: The total number of events collected and that pass our 3D and 2D selection filters (both with optical reconstruction filters applied), along with the expected background of non-beam-induced interaction events. We see clear excess from both filters, with a higher purity sample in the 3D-based selection sample. The results here use an integrated protons-on-target of 1.86×10^{18} from the BNB. Uncertainties on the background are only statistical.

- The longest track in the reconstructed interaction must have a relative small angle ($\cos\theta < 0.85$) with respect to the beam axis, reducing the likelihood an incoming cosmic-ray muon can fake our selection.

We validate the cosmic-event background rate in our neutrino beam data by analyzing events that contain flashes that are out-of-time with the beam spill and by running the TPC reconstruction and selection on events that have no beam data (cosmics-only datasets). From these two datasets, we obtain the background rate for events that pass a looser version of the optical reconstruction selection described in Section 2.1—where we allow events with flashes between 0 and 10 μs after the event trigger time—for the 2D and 3D selection criteria. For the 3D selection, we find this rate to be 0.010% ± 0.003%, while for the 2D selection it is 0.87% ± 0.03%. We see that the 3D selection has a lower background rate than the 2D selection, but it is also expected to have a lower neutrino-interaction signal efficiency, due to the strict requirement on observing a fully-contained interaction.

2.3 Results of the automated selection

The number of events recorded and passing the selection requirements described in Sections 2.1 and 2.2 is shown in Table 2.3. In total, after collecting events over which the BNB delivered 1.86×10^{18} protons on target, 18 (463) events passed the 3D (2D) selection and were identified as neutrino interaction candidates candidates in the first 24 h of running. The selection was designed to enrich the final sample with neutrino interactions— we expect that roughly 75% of the events are neutrino interactions in the 3D-based selection sample—but, in order to obtain high purity in this analysis we have sacrificed our overall acceptance of neutrino interaction events. This event total does therefore not reflect the total number of neutrino interactions observed in the detector. Further studies will increase and measure the neutrino-interaction selection efficiency, and allow measurements of $\nu-$Ar interaction cross sections.

3 First neutrino event displays

We show event displays of some of the events that pass our selection requirements in Figures 2-8. These displays, along with MicroBooNE's collection of publicly release material, can be found in [4].

4 Conclusion

We have identified neutrinos from the BNB interacting inside the MicroBooNE detector using, for the first time for a LArTPC, a fully-automated reconstruction and event selection. The data was recorded in the first week of the start of the BNB after an accelerator maintenance shutdown, and the data was reconstructed and analyzed with use of the LArSoft software framework. We have shown that we are able to reconstruct signatures of neutrino interactions both drifting ionization electrons observed by the wires of the TPC as well as scintillation light produced in the ionization of liquid argon. We have also shown, despite very large cosmic-ray-induced backgrounds, we are able to perform an automated selection of a sample of events that contain neutrino interactions, and do so at relatively high purity. Our ability to do these crucial tasks is the foundation for the future physics program of MicroBooNE.

5 Acknowledgements

We would like to acknowledge the support of Fermilab, the Department of Energy, and the National Science Foundation in the construction, operation, and data analysis of MicroBooNE.

References

[1] The MicroBooNE Collaboration, *Technical Design Report*, `http://www-microboone.fnal.gov/publications/TDRCD3.pdf`, February 2011.

[2] The MicroBooNE Collaboration, `http://www-microboone.fnal.gov/first-tracks/`, August 6, 2015.

[3] E. D. Church, "LArSoft: A Software Package for Liquid Argon Time Projection Drift Chambers," arXiv:1311.6774 [physics.ins-det].

[4] MicroBooNE Website:
`http://www-microboone.fnal.gov`.

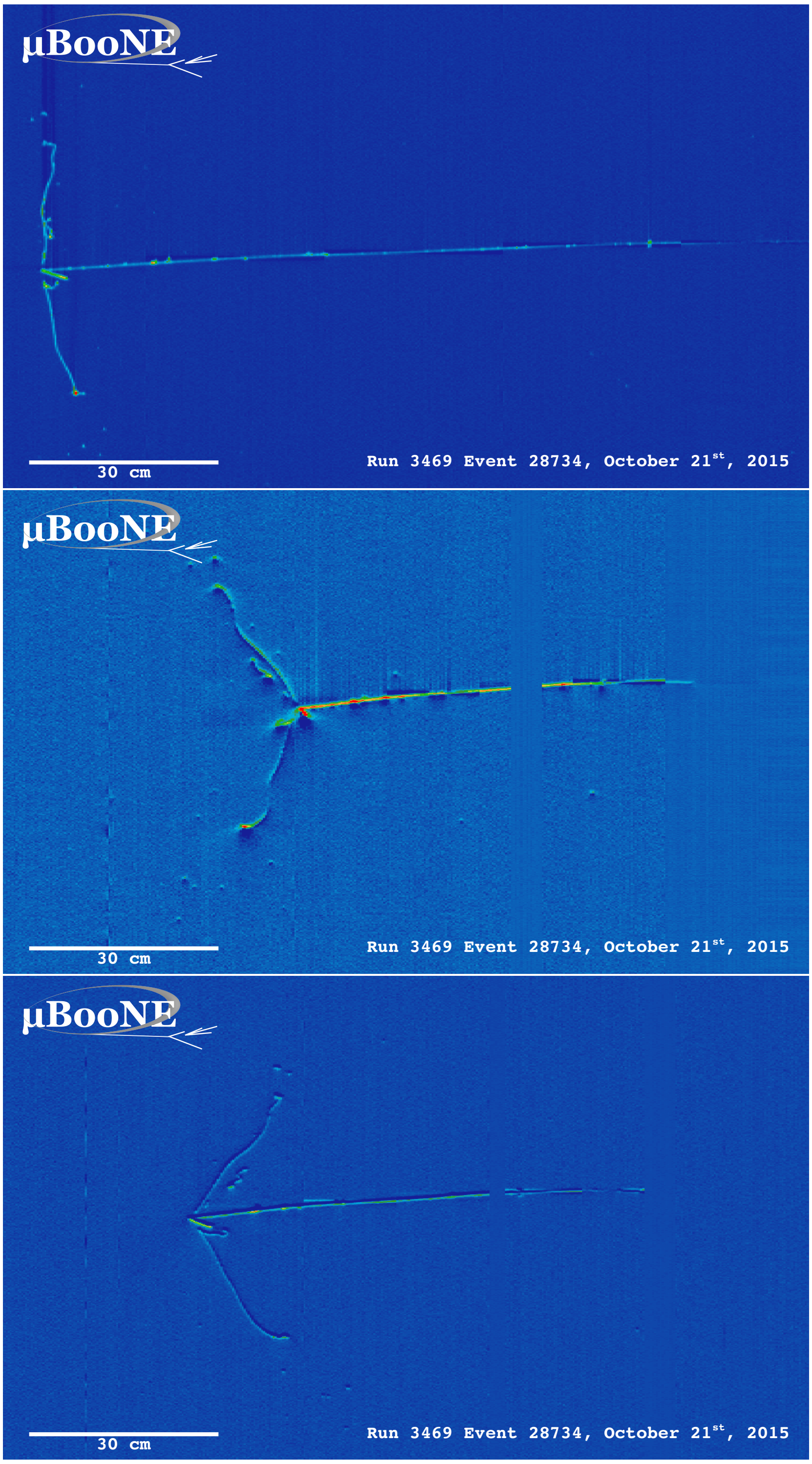

Figure 2: Neutrino interaction candidate event from MicroBooNE. Run 3469, event 28734, collection plane view (top), first induction plane view (middle), and second induction plane view (bottom). This event passed the optical + 3D-based TPC selection.

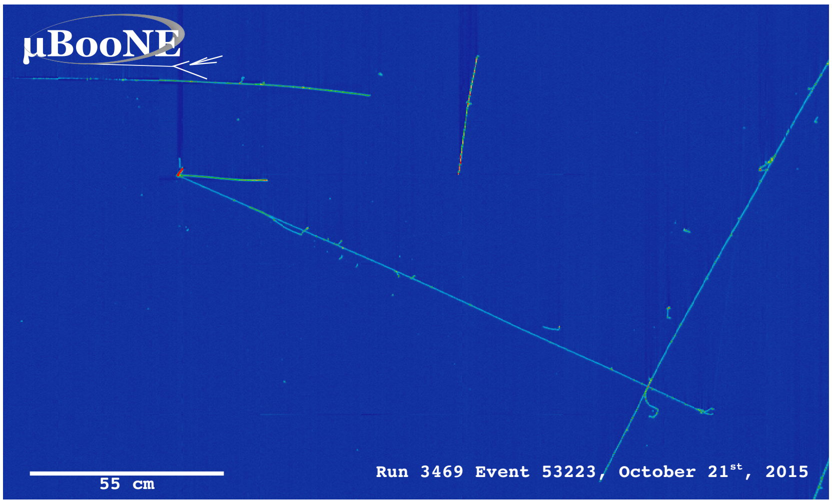

Figure 3: Neutrino interaction candidate event from MicroBooNE. Run 3469, event 53223, collection plane view. This event passed the optical + 3D-based TPC selection.

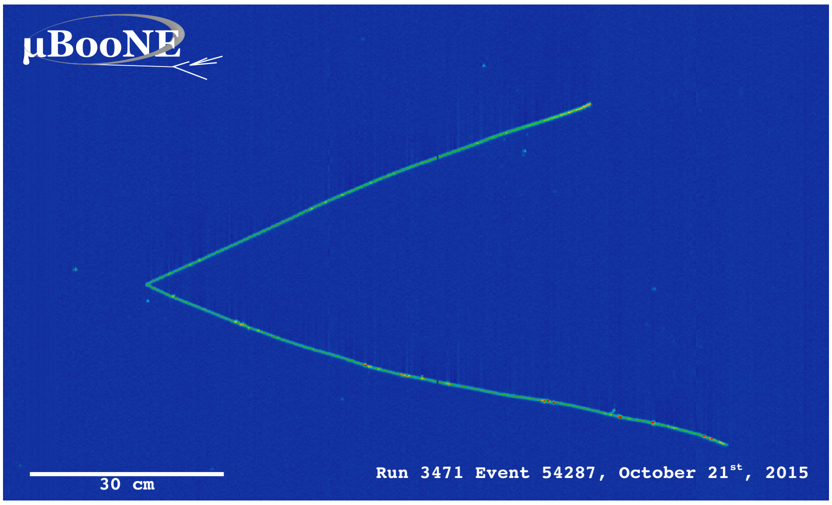

Figure 4: Neutrino interaction candidate event from MicroBooNE. Run 3471, event 54287, collection plane view. This event passed the optical + 2D-based TPC selection.

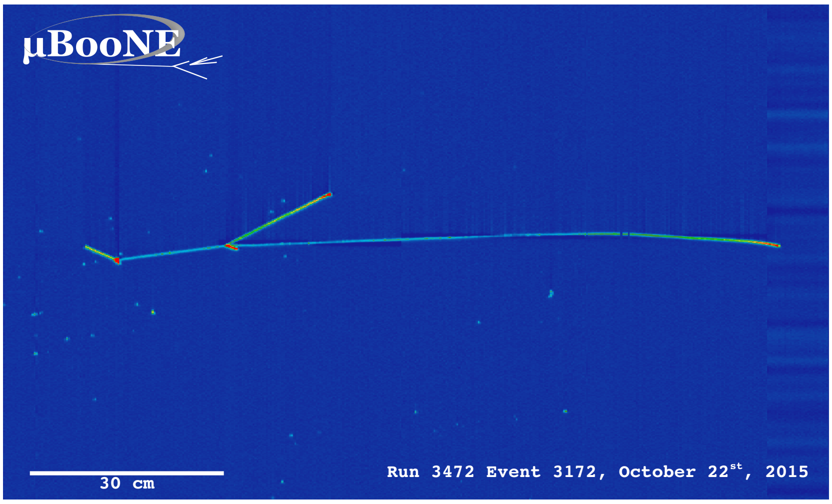

Figure 5: Neutrino interaction candidate event from MicroBooNE. Run 3472, event 3172, collection plane view. This event passed the optical + 2D-based TPC selection.

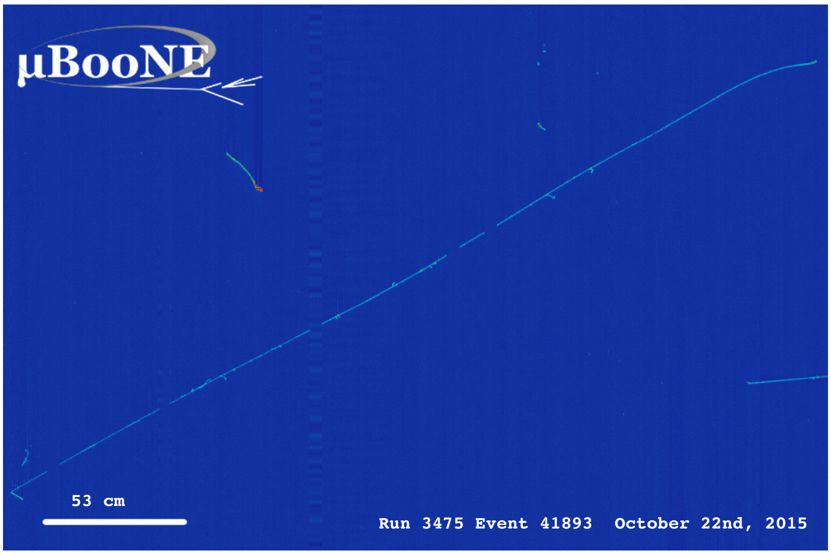

Figure 6: Neutrino interaction candidate event from MicroBooNE. Run 3475, event 41893, collection plane view. This event passed the optical + 2D-based TPC selection.

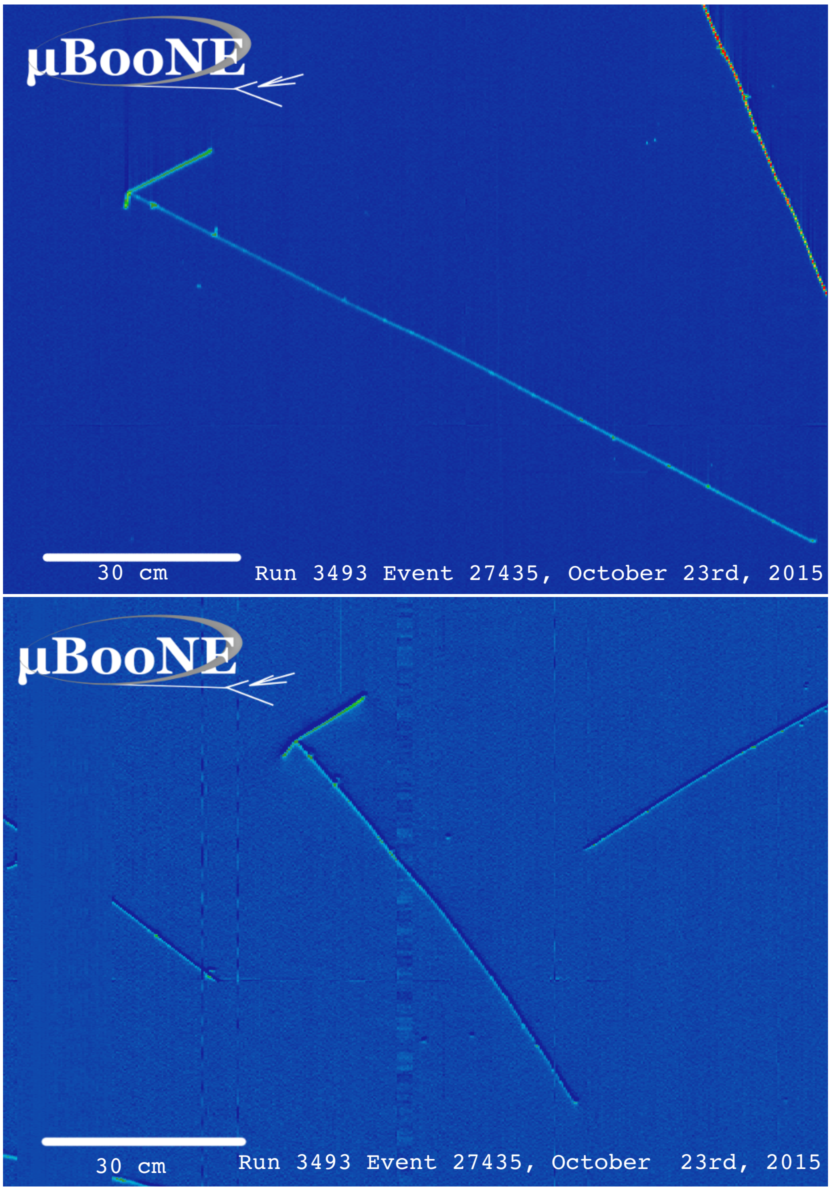

Figure 7: Neutrino interaction candidate event from MicroBooNE. Run 3493, event 27435, collection plane view (top) and second induction plane (bottom). This event passed the optical + 2D-based TPC selection.

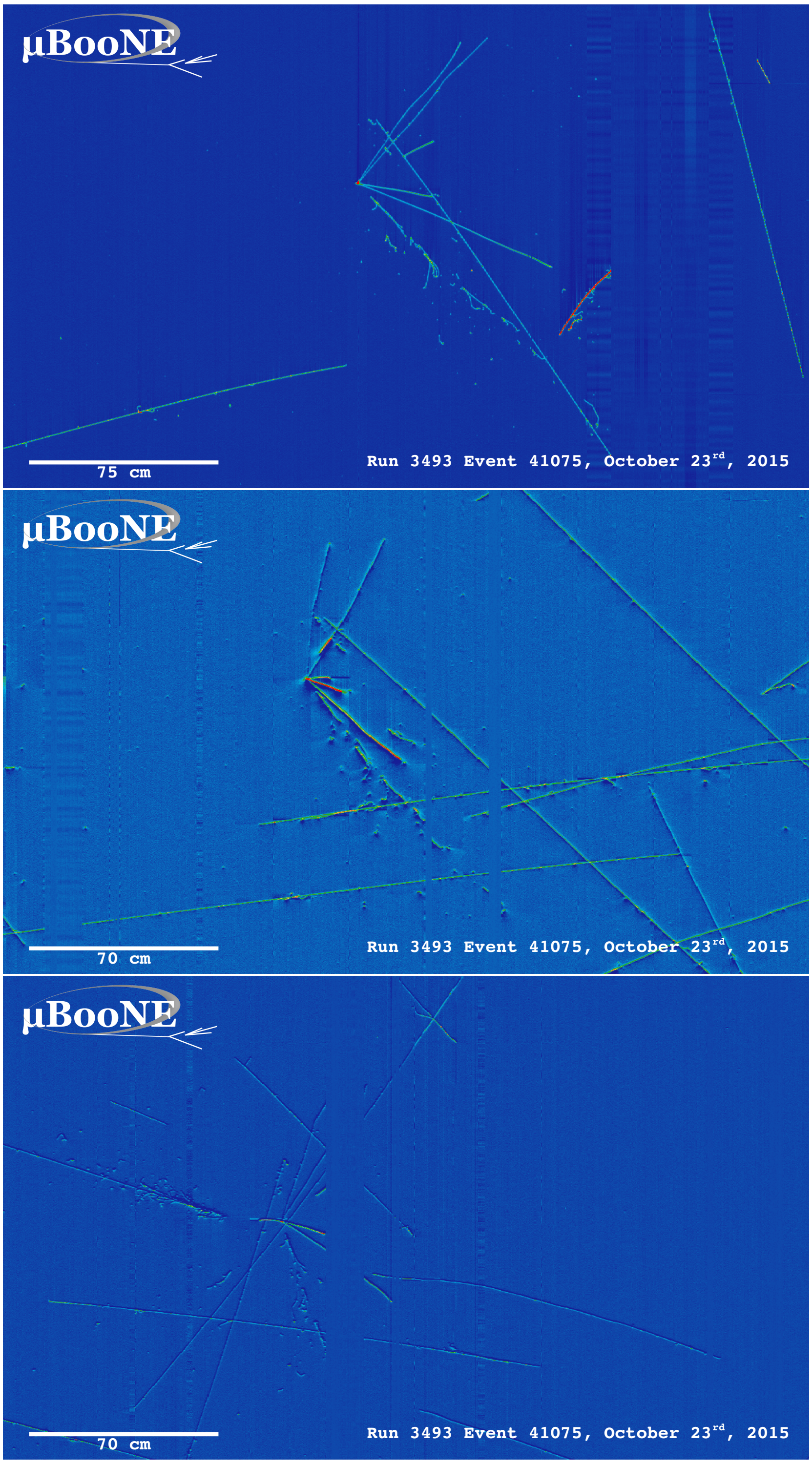

Figure 8: Neutrino interaction candidate event from MicroBooNE. Run 3493, event 41075, collection plane view (top), first induction plane view (middle), and second induction plane view (bottom). This event passed the optical + 3D-based TPC selection.