Finding first neutrino events with MicroBooNE

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Abstract

We present an analysis for identifying a purified selection of neutrino interactions from our large cosmic ray backgrounds using the first days of BNB data from MicroBooNE. This selection is aimed at providing events that can be shown in our approved event displays and released publicly in a timely manner. Since event rates for 5 Hz running of the BNB are large and cosmic background events will outnumber neutrino interactions by far, an automated procedure is necessary to select neutrino candidate events. We show this can be achieved based on the timing information of flashes observed by the PMT system and topology of events reconstructed in 2D and 3D from TPC information. Based on these studies, we believe an automated selection that will provide us with a rate of O(100) events per day (assuming nominal rate and POT per pulse from the BNB), where the cosmic background contamination is on the order of 20%. We use the procedures developed in this analysis to further study expected signal and background rates from data and simulation, and apply the filters described here to extract the first neutrino interaction events for MicroBooNE. Using our 3D TPC selection requirements, we obtain a sample of events with roughly 30% contamination from cosmic ray events.

1 Introduction

1.1 Goal

The goal of this analysis is to positively identify Booster Neutrino Beamline (BNB) neutrino interaction events in the MicroBooNE detector in data collected during the first day(s) of running. Events will need to be (1) identified as likely neutrino interaction events, and (2) separated from the large "empty-beam-spill" and "cosmic-coincident-beam-spill" backgrounds. The former will be done by identifying events with a detected flash of scintillation light during the 1.6 μs beam-spill length of the BNB, and by identifying reconstructed objects from the TPC that are consistent with being from a neutrino interaction. The latter will be done by rejecting events that do not have flashes of scintillation light during the beam-spill period, and/or that lack clearly identifiable neutrino-interaction-like topologies in the TPC reconstruction. After selection, events will be cross-checked in 2D and 3D event displays for verification of the selection performance, and to determine which event displays will be part of a near-term public release.

The selections defined here are targeted to reduce the ratio of readout events containing a neutrino interaction to readout events that contain only cosmic backgrounds from an initial ratio of 1 neutrino to 675 backgrounds to a ratio of 1 to 0.5 or better (rates are explained in the following subsection). This is equivalent to reducing the background of cosmic events by a factor 1000 or more. At this level, the total number of events passing selection will be in the few hundreds per day. From that point, if further separation of neutrino events from cosmic-only background events is necessary, events from the first days of data-taking that pass these automated filters can be confirmed and distinguished from cosmic events by studying event displays.

The selection of events from this analysis are intended to be used for MicroBooNE's first public displays of neutrino interactions. Therefore, we want to select events which are clearly identifiable as a neutrino interaction by not only MicroBooNE collaborators, but also colleagues from other experiments and the public. These events should show a clear interaction vertex with at least two tracks originating from it, and a flash of scintillation light that is coincident with the BNB beam-spill period. This analysis is not optimized for obtaining a high-efficiency or ultra-high-purity sample of neutrinos, which may be determined in later studies.

1.2 Event rates

At the start of this report, we are introducing the following definitions that should help the understanding of the studies presented below.

- **Readout event**: an event of 4.8 ms length that gets read out whenever we receive an accelerator timing signal. The trigger for the readout occurs at 1.6 ms (3200 2-MHz samples) into the readout event time. The readout event may or may not contain a neutrino interaction.

- **Neutrino event**: a readout event that contains a neutrino interaction.
- **Cosmic event**: a readout event that does not contain a neutrino interaction but only cosmic background tracks and showers.
- **Accidental**: A flash which was not induced by the beam, but occurred during the 1.6 μs beam spill. Includes all backgrounds such as noise, cosmic particles (other than muons), and possible radioactivity.

This paragraph shows a very simple calculation on how many neutrino interactions we can expect in MicroBooNE.

- A booster spill has $4 \cdot 10^{12}$ POT.
- If we are running with 5 Hz, we will therefore get $1.7 \cdot 10^{18}$ POT per day.
- Based on MCC6.1 simulation, we know that 20,000 neutrino interactions in the full active volume of the MicroBooNE TPC (87 tons) corresponds to $5.3 \cdot 10^{19}$ POT[1].
- This results in roughly 650 neutrino interactions per day in the TPC active volume.
- In other words: we will have about 1 neutrino interaction per 660 beam spills.

Note that these calculations include all interaction types and all neutrino flavors, and do not assume a fiducial volume cut.

Another important number to take into account in the following is how many cosmic muon background tracks are observed in a drift window. The expected number of cosmic ray induced tracks per readout window, from studies by Matt Bass (DocDB 4742) and Sowjanya Gollapinni (DocDB 4751), are listed below.

[1] taken from CC incl. study, see DocDB 4633.

Drift HV (kV)	Drift time (ms)	CRY sim (muons)	CORSIKA sim (muons)	Data (handscan)	Data (reco tracks)
-58	2.6	9.9	14.3		
-70	2.3	8.8	12.7	10.1	7.3

Table 1: Expected cosmic rates per readout window. These numbers come from studies presented in DocDB 4742. The data "handscan" results (DocDB 4742) find an average of 10.1 track-like objects in 50 data events after extrapolating down from the full readout window (4.8 ms) to a 2.3 ms drift time. The data "reco tracks" results come from looking at *trackkalmanhit* 3D-reconstructed tracks in cosmics data. The numbers, roughly, agree.

The rate changes with the applied cathode voltage because the drift time changes with the electric field strength. The summary of expected rates from simulation and a hand-scan of data are shown in Table 1.

A short note on background from neutrino interactions in the dirt outside of LArTF: Studies by Katherine et al. have estimated that the rate of events that do have traces from dirt interactions inside the TPC active volume is 81 per 1.7e16 POT (corresponding to one hour of running at 5 Hz). However, only 2 of these 81 events are expected to have muon track fragments inside the TPC active volume. This is a small background that has not been further studied in this note. We expect that, since the topology cuts defined below are looking for a neutrino vertex inside the active volume, the dirt event contamination after TPC-based selection should be small, as incoming muons should not appear contained. Meanwhile, dirt events will help pinpoint flash-timing studies by increasing the number of flashes seen in-time with the beam spill.

1.3 General strategy

The general strategy for the analysis is as follows:

1. Identify flashes from scintillation light produced in-time with the beam spill. Reject events that do not have such a flash.

2. On remaining events, perform 2D and 3D reconstruction, utilitizing clustering, tracking, and vertex-finding algorithms to identify neutrino-interaction-like topologies. Reject events that don't contain these neutrino candidates.

For events that do, distinguish them from other cosmic rays in the event.

The optical- and TPC-based reconstruction and selection filters are separate, allowing for individual evaluation of them. They are described in Sections 2 and 3, respectively. Section 4 contains a more detailed description of the exact data-processing strategy, with an overview of the expected number of events after each step of the filtering.

The results presented in this note are currently derived from a variety of different sources: cosmics data, and Monte Carlo simulation with cathode voltage at -128 kV and -70 kV. In particular, analysis of the flash-finding has produced expected filtering rates based on data; meanwhile, the TPC reconstruction has based most of its expected rates on simulation with cathode voltage at -128 kV.

Additionally, as a collaboration we are still moving towards stable and well-performing reconstruction algorithms that properly handle the complicated noise behavior seen in the data from the detector. Thus, we expect there may be some changes, especially in TPC reconstruction, that may affect exact purities and efficiencies. Since our assumptions throughout are usually conservative, we do not expect changes in the reconstruction software to alter the end conclusions much.

2 Flash Finding

This section describes the first event filter to be applied based on reconstructed optical information, namely optical flashes. Technical details of data samples used and analysis scripts as well as LArSoft event filters to be used are described in the last part of the section.

2.1 Flash Reconstruction

Flash reconstruction is described in detail in Ben Jones's thesis (DocDB 4736). A flash is defined as the collection of light observed at the same time across the detector. Flashes are reconstructed by first identifying optical hits: signals on individual optical detectors above a specified photoelectron (PE) threshold. Optical hits from all the PMTs are accumulated in 1μs bins of time, and if a bin rises above a set PE threshold, the collection of hits in that bin that overlap in time are defined as the ones that make up a flash. Properties of the flash—average time, average z and y positions and widths, etc.—are determined based on the set of hits.

The total size of a flash is described by the number of photoelectrons in the flash in total (summed over all PMTs in the flash). Neutrino interactions and cosmic muons are expected to produce a significant amount of light, however accidentals such as cosmogenic secondaries, noise, and other low energy backgrounds (many of which are not modeled in MC) will produce flashes with very low PE. For this reason cutting on the number of PEs in a flash is a good way of removing many backgrounds.

The number of PE distribution over all cosmic MC flashes is shown in figure 1. MCC 6.1 was used.

2.2 Flash Finding Efficiency

Using BNB Monte Carlo simulation, the flash finding efficiency for neutrino interactions was estimated. Figure 3 shows the efficiency for finding flashes as a function of the minimium PE in a flash, and figure 4 shows the same but zoomed in to the most interesting region. As is expected, with no minimum PE requirement the efficiency is close to 100% (the inefficiency coming from attenuation, PMT intrinsic efficiency and other effects). Requiring a minimum of 50 photoelectrons in a flash still retains 81.9% of beam interactions. This efficiency is expected to be sufficient for this analysis, though more sophisticated cuts may be developed in the future.

Figure 5 shows the efficiency for finding flashes from beam events, as a function of the beam interaction point in the x-direction (corresponding to the distance from the wall of PMTs). The efficiency looks rather flat for $x < 100$

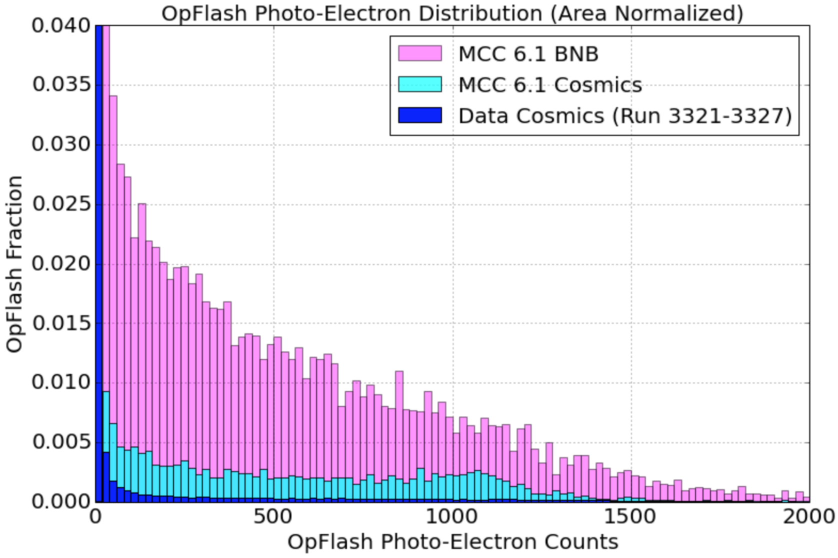

Figure 1: The distribution of number of PE in each flash. MCC 6.1 BNB, Cosmic, and Data are overlayed where data is taken from runs 3321-3327. For MC BNB distribution the flashes are taken from the 1.6 μs beam spill window, and cosmics are taken from 3 ms window. Distributions are then normalized within the shown range of Flash PEs. The majority of flashes from cosmogenic sources are small compared to the typical neutrino flash amplitude, and could be cut out with a moderate PE cut.

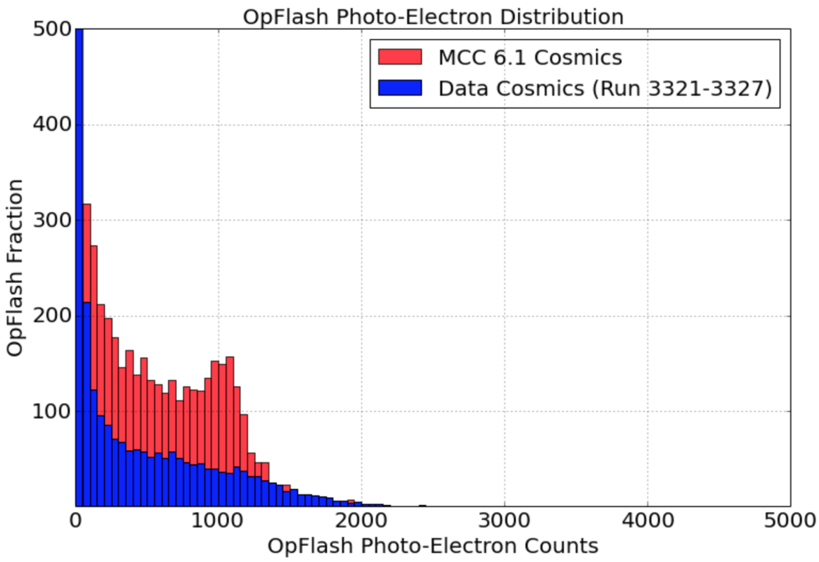

Figure 2: The distribution of number of PE in each flash. MCC 6.1 Cosmic, and Data are overlayed where data is taken from runs 3321-3327. MC is scaled to the same number of events that were recorded in this data run.

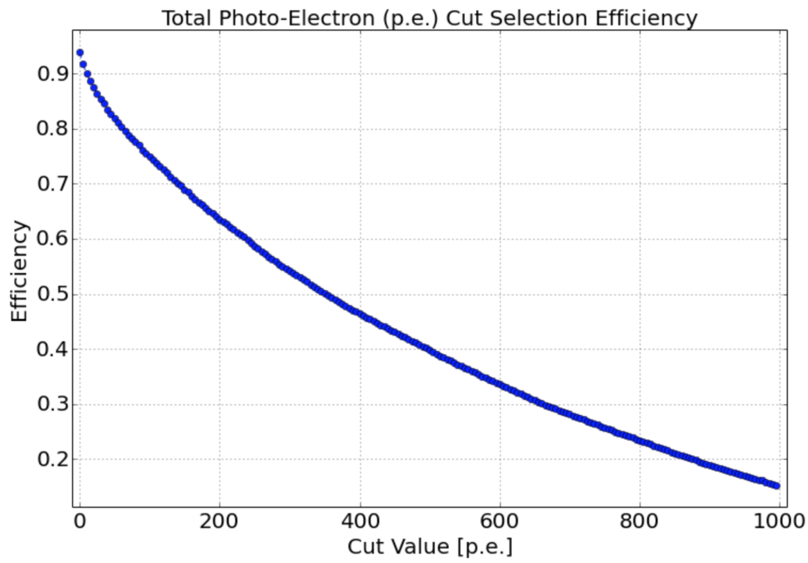

Figure 3: Efficiency for selecting beam events as a function of minimum PE cut.

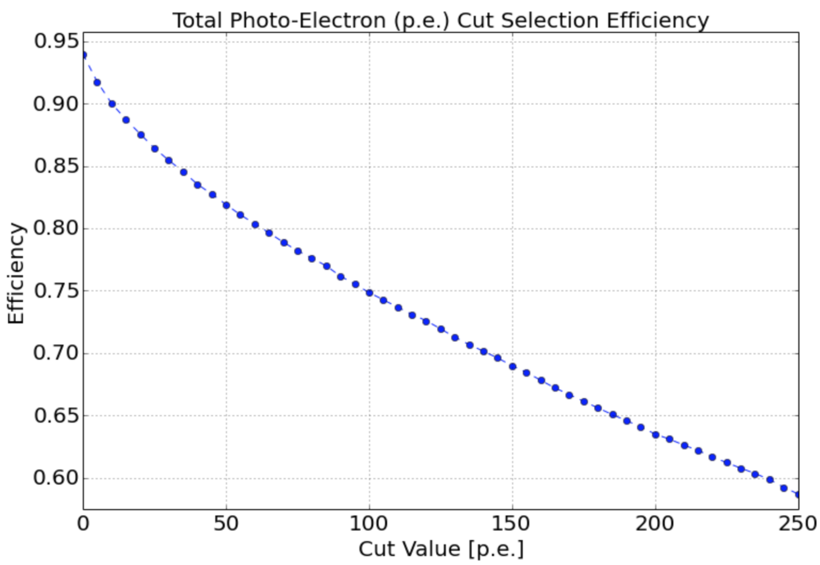

Figure 4: Efficiency for selecting beam events as a function of minimum PE cut. Zoomed into most interesting region. Note the efficiency does not hit 100% with as the cut PE drops to zero due to attenuation, PMT intrinsic efficiency and other effects.

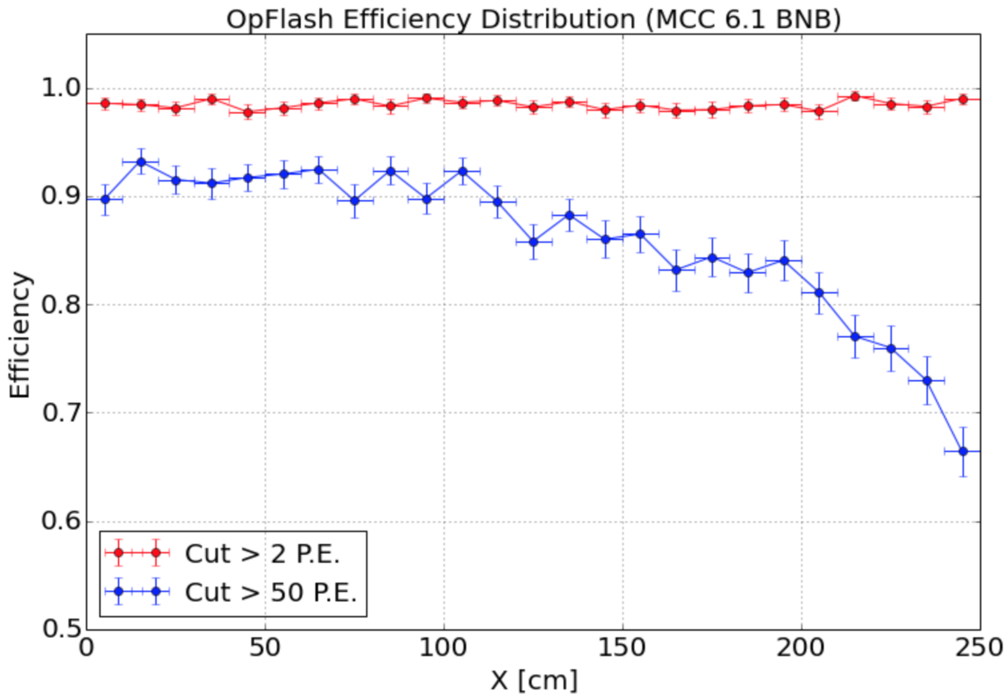

Figure 5: Efficiency for selecting beam events as a function of x-position (in cm) of the flash, for a 2 PE, and a 50 PE threshold cut.

cm, with some slight reduction in efficiency as the events get close to the far edge of the TPC.

2.3 Cosmic Mis-ID

A cosmic "mis-ID" will occur when a flash from a cosmic happens to overlap with a beam spill search window. It is also in principle possible to have dark noise hits in coincidence, however this is expected to be a negligible contribution. It is clear from figure 1 that there is a very large accidental contribution at low PE values which is removed by a very moderate PE cut.

Unfortunately, as figure 2 shows, there are some substantial differences between the MCC6 6.1 cosmic MC and recently collected data. However, some differences are expected: for example, the drift field in data is lower and the purity is higher, which should lead to more light being collected by the PMTs in data.

Also, there is some evidence that the liquid argon filters release small amounts of radon into the cryostat [2, 3], in which case some of the flashes in data will come from radon decays, however these flashes are also expected to be small, and a moderate PE cut will remove these events.

Taking into account the above considerations, we feel a moderate PE value will remove a large fraction of accidental and cosmic events, without significantly reducing the number of neutrino events.

Figure 6 shows the measured mis-ID rates as a function of PE threshold for cosmic data and MC. Clearly most flashes from non-beam backgrounds are very low energy, so for the same 50 PE cut which achieves an overall 80% neutrino selection efficiency, almost all of the accidental backgrounds are removed, leaving 0.8% of events with a flash due to non-beam background. This number agrees with the prediction one would get using the cosmic ray-induced tracks observed in data (see Table 1). For 8 observed tracks in a 2.3 ms drift window, we would expect $8 \times \frac{1.6}{2300} = 0.0056$ cosmics during the 1.6 μs beam spill. It is not surprising that long cosmic muon tracks would leave in excess of 50 PE in the reconstructed flash.

2.4 Beam Timing

An essential component for a filter using flashes is to get the appropriate time from the flash, and make a cut restricting flashes to be consistent with the neutrino beam spill period. As mentioned previously in Section 2.3, requiring a flash with $N_{\mathrm{PE}} > 50$ that is in time with the 1.6 μs BNB spill period will reduce the number of events by a factor of more than 150. However, before we can make a cut on flash timing, we must understand the timing of the trigger and PMT readout relative to the arrival of neutrinos from the BNB. While efforts have been made to understand this timing during commissioning, the best way to verify this timing is to identify a 1.6 μs window near the expected beam-time (which is a few μs after the trigger time) where the number of flashes is significantly above the cosmic-ray background.

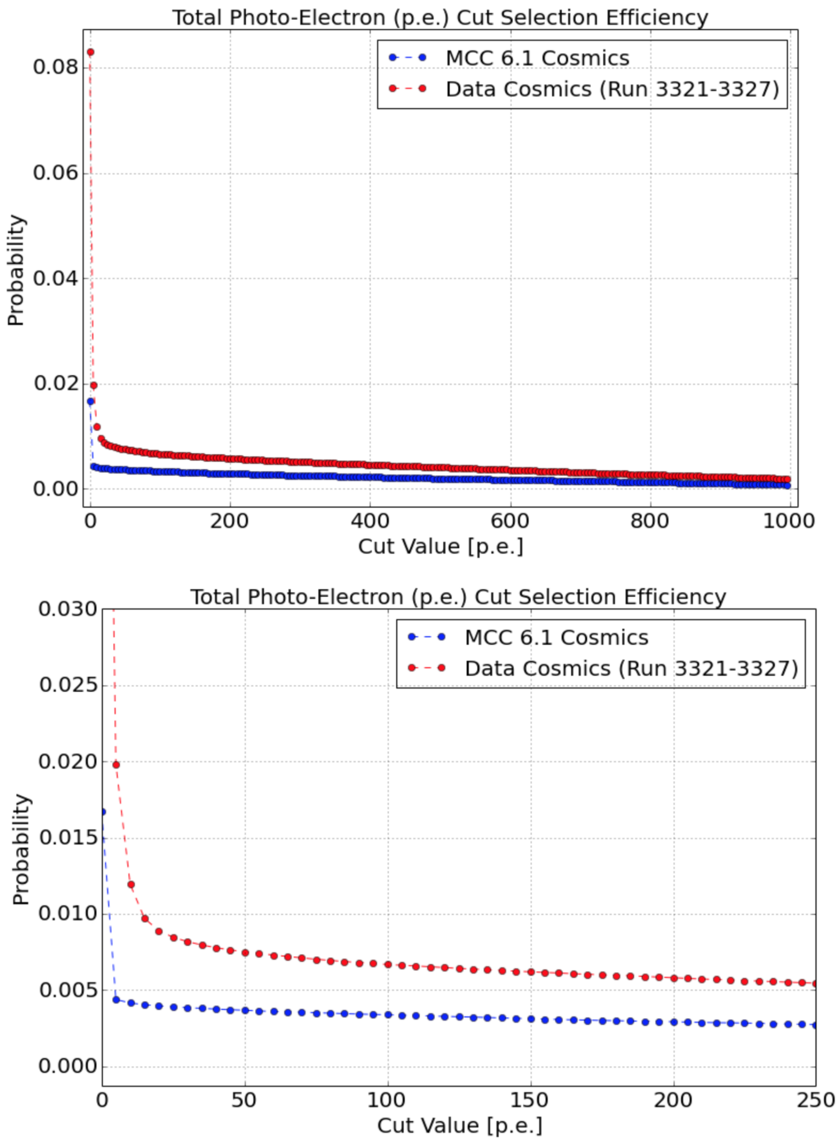

Figure 6: Fraction of cosmic events with a flash in the beam spill period as a function of the minimum PE of that flash, for (blue) MC and (red) data.

2.4.1 RWM timing

From an understanding of the RWM signal at MiniBooNE, we expect the neutrino spill to begin between 1 and 2 μs before the RWM signal is received. Figure 7 shows the time of arrival of the RWM signal with respect to the trigger. A tight distribution around 5.7 μs after the trigger is seen. The 100 ns width of this distribution is expected from the natural "jitter" of the accelerator trigger signals.

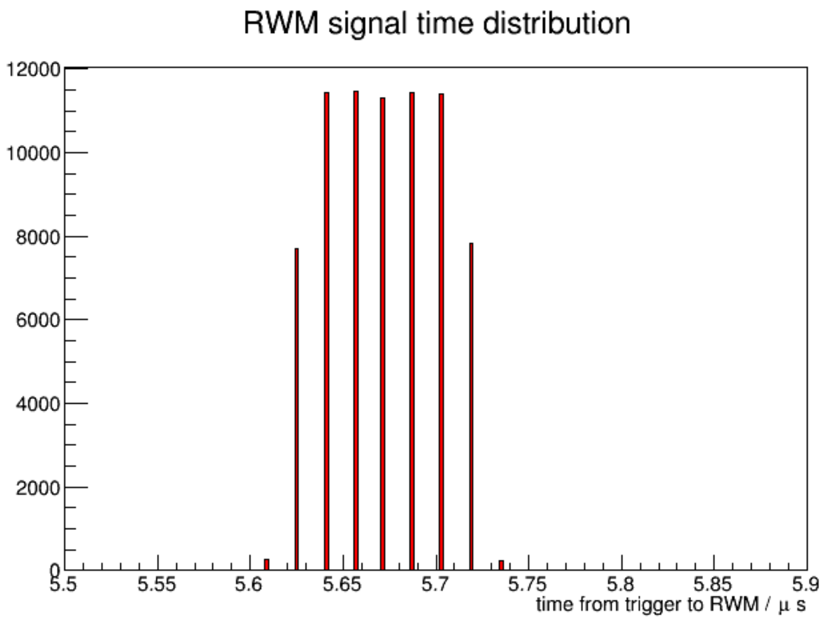

Figure 7: The time of the RWM signal with respect to the trigger. A 100 ns wide distribution around 5.7 μs after the trigger can be seen. This 100 ns width comes from intrinsic "jitter" from the trigger signals. The discrete nature of the arrival times is due to the clock sampling frequency.

2.4.2 PMT flash timing

First: a quick note on the PMT readout, which is explained in more detail in [4]. Unlike the case for the TPC wires, we do not get unbiased readout over an entire drift period (or number of drift periods) from the PMT readout system. Instead, we receive short windows of readout in one of two ways: (1) from individual PMT channels going above a set "discriminator" threshold; and, (2)

Reconstruction algorithm	Minimum PE cut	Flashes per 0.3 μs per 1000 events
"OpFlash"	50	31.1 ± 0.44
	200	23.3 ± 0.38

Table 2: Measured cosmic background rates, using different PE cuts.

Integrated POT	1.78×10^{18}
Number of triggered events	1.19×10^{6}
Number of swizzled events	1.08×10^{6}
Events passing 50PE cut in 0-10 μs window	55445

Table 3: Important quantities for the optical filtering analysis. The reason the number of swizzled events does not match the triggered events is due to a 10% failure rate of submitted jobs.

from all PMT channels when an input signal, like a beam gate or fake beam gate, is sent into the PMT readout boards. This latter form provides unbiased readout of the PMT channels, and we expect to obtain this unbiased readout for a period of 23.4 μs after the trigger time.

The cosmic rate was measured using data runs 3321, 3322, and 3327, in which there was no BNB data. Reconstructed flashes with more than 50 photoelectrons in a given 0.3μs window (during the beam-gate readout) were counted, and as a cross check the rates were compared with a 200 photoelectron cut.Table 2 shows the values obtained from this high-statistics sample. These values can be scaled to determine the expected cosmic background rate in the beam-on sample used later.

As beam data was collected, files were swizzled and optical flash reconstruction was run. Runs where the mean protons-per-pulse (ppp) in the BNB was above 1×10^{12} were used to search for an excess of neutrinos above the cosmic ray background. The data used for this timing measurement was taken during the first week of running between October 16th 2015, and October 22nd 2015. Table 3 details various important quantities related to this data.

The total POT used is roughly equivalent to 24 hours of data taking at nominal intensity (4×10^{12} ppp) and 5Hz repetition rate. Figure 8 shows the size of the expected neutrino signal in this time from Monte Carlo simulations. In the real data used, the intensity is lower, however we still observe a significant

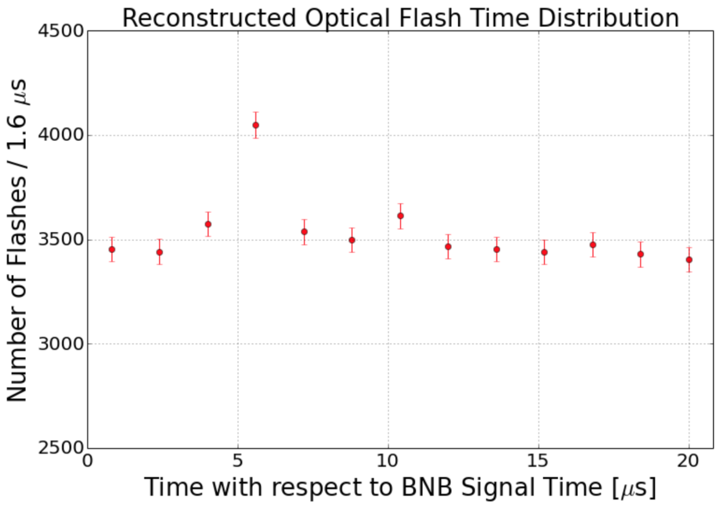

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Figure 8: Predicted distribution of flash times, with respect to the trigger time, for 1 day (24 hours) of data taking at nominal rate and intensity.

excess above data, as shown in figure 9.

2.5 Event Rates After Flash-Finding Filter

We expect about 5%[2] of cosmic-ray events to survive a filter that requires a flash with $N_{\mathrm{PE}} > 50$ to be inside a 10μs-long selection inside the unbiased beam readout window of the PMT readout. Further reducing the time-selection to 1.6μs reduces the cosmic-ray event survival probability to 0.8%, as noted in Section 2.3. Assuming a 5 Hz beam rate, this will leave 2100 and 135 cosmic-ray events per hour passing the flash-finding filter, respectively. The efficiency for neutrino events to pass the flash amplitude and timing filter is, as noted in Section 2.2, 82%. Using the rough numbers offered in Section 1.2, we expect about 650 total neutrino events per day, and thus would expect about 22 neutrino events per hour to pass this filter.

2.6 Technical Remark

In this section three kinds of event samples were used.

[2]Obtained by scaling up the 0.8% for 1.6 μs to 10 μs

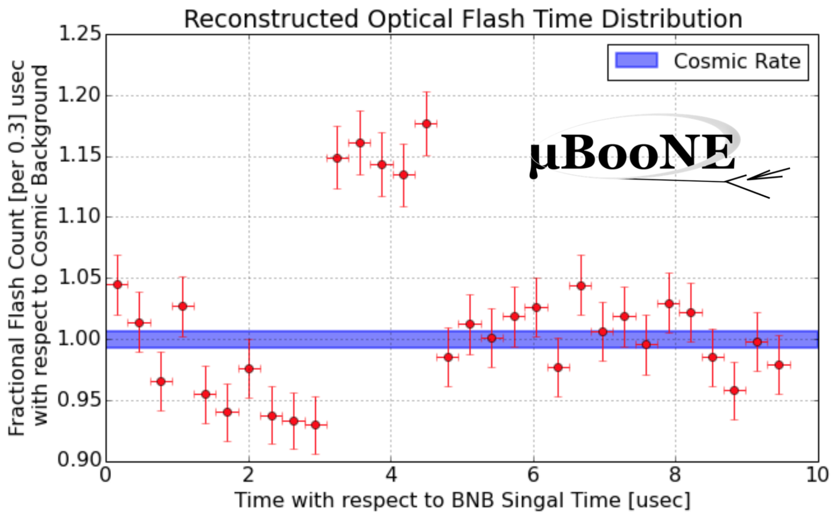

Figure 9: The measured distribution of flash times (requiring flashes greater than 50PE) with respect to trigger time, shown as a ratio to the expected cosmic rate from off-beam data. A clear excess can be seen due to neutrinos between 3 and 5 μs after the trigger. This is where the neutrinos were expected based on the RWM signal arrival time.

1. MCC 6.1 BNB Monte Carlo simulation
2. MCC 6.1 Cosmic Monte Carlo simulation
3. Cosmic data sample from run 3321, 3322, and 3327

Data files for above samples can be found under the persistent dCache area:

```
/pnfs/uboone/persistent/users/uboonepro/NeutrinoID_OpFlashData/
```

The actual list of events, identified by a combination of run, subrun, and event id, are generated from data file themselves and stored in the git repository. Data files are output of an actual LArSoft filter module that can be found under MicroBooNE software repository, uboonecode:

```
uboone/OpticalDetectorAna/FlashTrigger_module.cc
```

The event list text files can be found under the sub-directory:

```
uboone/OpticalDetectorAna/opflash_ana_neutrino_id
```

under which following analysis scripts, used to generate plots in this section, can be found as well.

EventListPrintOut.ipynb ... Generate event list text files.

FlashFilterEfficiencyAnalysis.ipynb ... Fig.3,4,6.

FlashTimeAnalysis.ipynb ... Fig.8.

FlashXDependency.ipynb ... Fig.5

3 TPC topology selection

In order to further reduce the background of cosmics events to our neutrino event selection, and to select neutrino events that are suitable for first public displays, we need to make use of reconstruction of the data from the TPC wires. We have developed two independent selection streams that use information from the TPC: one based on reconstructed 2D clusters, and the other based on reconstructed 3D tracks.

The main idea is the same in 2D and 3D. It is to look for a neutrino interaction inside the TPC active volume, which can be identified by two or more tracks originating from the same vertex. An example event display is shown in figure 14. Additional requirements enhance the purity and are described below.

The advantage of having 2D and 3D channels running in parallel is that if the performance of a particular algorithm that we optimized for is bad on actual experimental neutrino data, we still have event candidates coming through the other channel.

The topology cuts presented below are currently optimized on MCC6.1 simulation, which was using 128 kV cathode voltage[3]. Processing of updated MC is still ongoing.

[3]The MCC6.1 files were generated with larsoft version v04_09_00 and are located in /pnfs/uboone/scratch/users/bcarls/cc_inc_mc/v04_09_00. All data sets (BNB only, Cosmic only, BNB + Cosmic) contain 20,000 events. If not stated otherwise, all events are used.

Note, that we are calculating passing rates for the TPC topology selection only. In addition, the number of background events will reduce by using flash finding as described above. In development, an approximate efficiency factor for cosmic events to pass the flash finding is the factor of 0.008 described in Section 2.5, which we are applying to the passing rates to give a feeling for final event numbers. This factor does not take into consideration correlations in the selection from the optical and TPC-topology information, and so thus is likely an overestimate on rejection rates, and should only be used as a general guide.

3.0.1 Cosmic tagging

The first step is based on the geometry cosmic tagging of events. The cosmic-ray-muon geometry tagger [1] runs on reconstructed 3D tags and assigns scores to each reconstructed track in the event that tag tracks that are most likely caused by cosmics.

Cosmic tagging scores for tracks:

- 1: the track is tagged as entering and exiting
- 0.95: the track is a delta ray associated with a tagged track
- 0.5: the track is either exiting or entering, but not both
- 0.4: the track is entering or exiting through the z boundary
- 0: the track is not tagged.

Clusters get assigned a cosmic score of either 0 or 1 accordingly.

Figure 10 shows that over 90% of cosmic induced tracks are tagged as cosmic. These tracks are not further considered when looking for neutrino topologies in an event. At the same time, we are losing about 20% of neutrino induced tracks by requiring that the events are contained.

In order to tag tracks as entering or exiting, the algorithm checks if the tracks go through a boundary region. The boundary region for this study was set to 5 cm distance from all sides of the TPC. Based on handscan studies with

Tracks	Tagged as neutrino (score = 0)	Tagged as "uncontained" (score > 0)
True neutrino	80.3%	19.7%
True cosmic	6.3%	93.7%

Clusters	Tagged as neutrino (score = 0)	Tagged as "uncontained" (score > 0)
True neutrino	100%	0%
True cosmic	31.1%	68.9

Figure 10: Matrix for tagging and mis-id'ing of neutrino and cosmic induced tracks in MCC6.1 with trackkalmanhit and cccluster (y-plane only).

recent experimental data, it has been decided to increase this boundary to 10 cm for all sides of the TPC, and we are going to use a 10 cm boundary for this selection. The 10 cm boundary has already been used for processing recent experimental data but not yet in any of the simulation used in this note.

Cosmic tagging is less efficient for clusters than for tracks, since full 3D-position information of the entering and exiting point of the cluster is not available. The rejection of clusters is mostly based on the timing information (reconstructed x position) of the cluster.

Since cosmic tagging is using the timing information of events to exclude every cluster or track that happens outside the drift window, it will depend on the drift time and therefore on the HV setting. The drift time at 128 kV is 1.6ms, at 70 kV it is 2.3 ms, so we are expecting about $2.3/1.6 = 1.44$ times more cosmic induced tracks or clusters in the drift window. Figure 11 shows a comparison of geometry cosmic scores for 128 kV simulation and data taken at 70 kV[4]. The cosmic tagging efficiency as seen from Figure 11 varies since several changes in the reconstruction between the two processing versions change also influence the result. From the comparison it can be said that there is no indication of any problem with cosmic tagging for lower drift fields.

[4]This data has been processed with v04_22_00 using RawDigitFilter instead of noise filter. MC at 128kV is from MCC6.1 and has been processed with v04_09_00. Files are located in `/uboone/data/users/aschu/CosmicTagging/CosmicTaggingComparison/`. The script to evaluate the tagging efficiency is in uboonecode feature branch `feature/Anne_NeutrinoIDFilter` in `uboonecode/uboone/TPCNeutrinoIDFilter/AnalysisScripts/ClusterVsTrackTagging.C`.

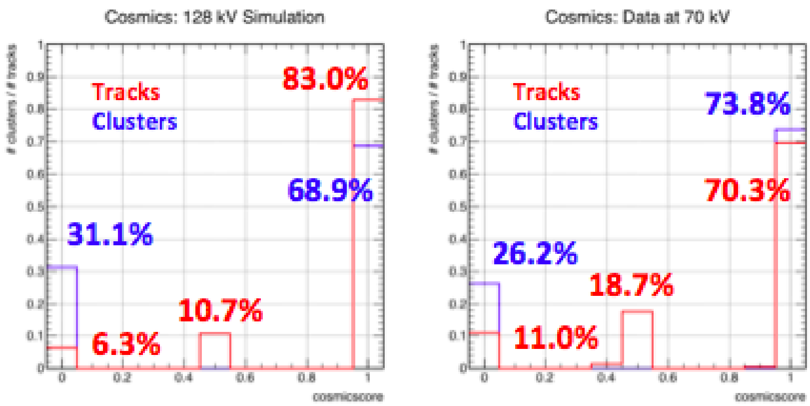

Figure 11: Cosmic scores for 128 kV simulation and data taken at 70 kV. Note that both have been processed with different versions. This is the reason why there are scores with 0.4 and 0.95 for the experimental data, this was not yet added when processing simulation. Histograms are area normalized to 1. Simulation uses 9200 events, data uses 180 events.

3.1 Selection based on 2D clusters

In first observations with experimental cosmics data, it has been shown that often 2D clustering performs reliably well, while the performance of 3D track reconstruction can be more sensitive to the performance of lower-level quantities, and thus performance can fluctuate strongly depending on, for example, different noise filters. This motivates having a neutrino selection filter running only on 2D objects, and in particular on clusters in the collection (Y) plane, which has the best information.

3.1.1 Primary Cuts

The first step is to determine which clusters to consider. We require that the clusters are in the Y-plane, the cluster cosmics tagger score was < 0.4 and the cluster had at least ten hits. We then select only readout events which contain at least two clusters that meet these requirements.

After the initial cosmic tagging has been applied, the following primary cuts are made to remove as many of the remaining cosmics as possible while leaving "nice"-looking neutrino events.

The next cut is made to remove long, vertical clusters. This cut was applied after going through cosmic events that are passing and seeing that most clusters are long and at high projected angles while the neutrino events are forward going clusters. We require a good cluster to have either a projected start angle less than 30 degrees from the z-axis or be less than 200 wires long. We add the length condition so that we do not cut any short high-angle clusters that may correspond to a proton, or other highly ionizing particle, accompanying a long muon cluster. The 200 wire length cut roughly equates to 0.6 m in the z-direction, assuming a 3-mm wire spacing. The projected cluster start angle, α, is defined by $\tan\alpha = \Delta T/\Delta W$, where T is time ticks and W is wires.

Lastly, we require all clusters to be at least 30 wire ticks or 30 time ticks long. This was a general cut to remove cosmics that were being matched with small deltas without removing short proton clusters that could be matched to a long muon cluster. We make the length cut in either the time or z direction because we don't want to remove more time-going short tracks. The reason that we don't cut out short tracks because our ideal neutrino events have both a long MIP cluster and a short, more highly ionizing cluster starting at the same point. This is explained in more detail in the next section.

3.1.2 Secondary Cuts

The goal of the secondary cuts is to match a long, low-angle cluster with a short, high-charge cluster. We only look at clusters that have passed all of the primary cuts. We first select a cluster with a length greater than 100 wires, which corresponds to approximately .3 m in the Z-direction.

We then search for any cluster which begins within approximately 3 cm (10 wires and 30 time ticks) from the low-Z end of the long cluster. We also require this cluster to be shorter than the initial cluster. Since start and end points of the clusters may be swapped, we compare both the start and end points of the shorter cluster to the point of the long cluster which has a lower wire value.

Cluster Set	No cuts	Primary cuts	Secondary cuts
Neutrino only	570	303	32
Cosmics only (no flash)	308,016	291,879	602
Cosmics only (with flash)	2464	2335	5
Neutrino/Cosmics	0.23	0.13	6.4

Table 4: Passing rates for 2D cluster cuts for a neutrino only MC set and a cosmics only MC set. Column one shows raw event rates with no cuts applied. Column two shows event rates after preliminary cuts are applied. Column three shows event rates after secondary cuts are applied. Line three shows the second line scaled with a factor of 0.008, which is a first guess efficiency estimate for the flash finding. All event numbers are normalized to events per day assuming we are running at 5 Hz.

This is to cut out backward-going interactions [5].

Now that we have a vertex match between a long and a short cluster, we make cuts on the charge and the projected opening angle of the pair. We require that the shorter cluster has a higher start charge than the long cluster OR that the longer cluster is longer than 500 wires. Start charge is defined as the charge on the first wire in ADC counts. We also require that the projected opening angle (the difference in projected start angles of the two clusters) be between 11 and 90 degrees. This cut is mainly to remove matched clusters which are either entirely overlapping or are actually part of the same long particle track.

The resulting neutrino/cosmic events per day are shown in table 4. Figure 12 shows in detail the percent of clusters that pass each primary cut. These numbers will be different than the number of events remaining because the cosmics have, on average, many more clusters per event than neutrinos. Figure 13 shows in detail the percent of matched cluster pairs remaining per secondary cut from the total number of events containing clusters that passed all primary cuts.

It is important to note that there is no 2D vertexing algorithm or flash matching used to calculate these numbers. Using a vertex algorithm rather than matching by hand as well as implementing flash matching may increase

[5] Analysis code can be found in uboonecode feature branch feature/Anne_NeutrinoIDFilter in the script uboonecode/uboone/TPCNeutrinoIDFilter/-AnalysisScripts/2DClusterNuCuts.C

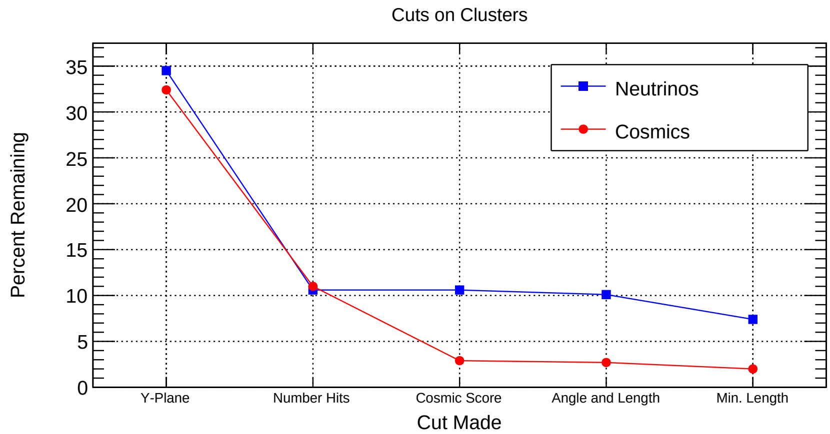

Figure 12: Percent of good clusters remaining for neutrinos and cosmics after primary cuts. The is relative to the total number of initial clusters.

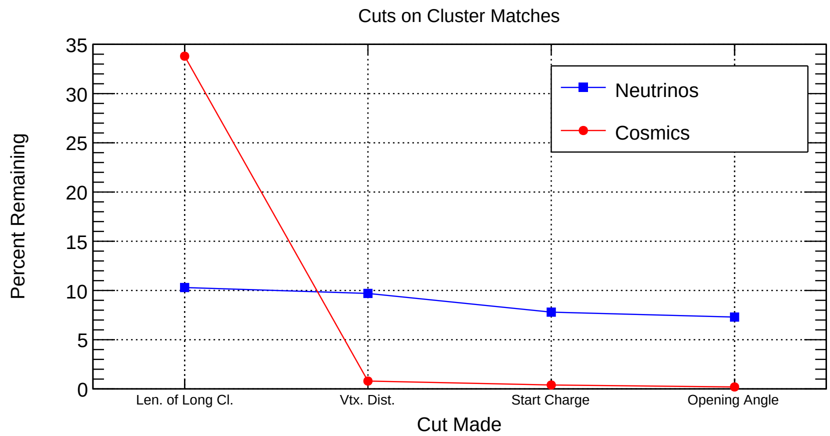

Figure 13: Percent of matched cluster pairs remaining for neutrinos and cosmics after secondary cuts. This is relative to the total number of events that contain clusters which pass the primary cuts.

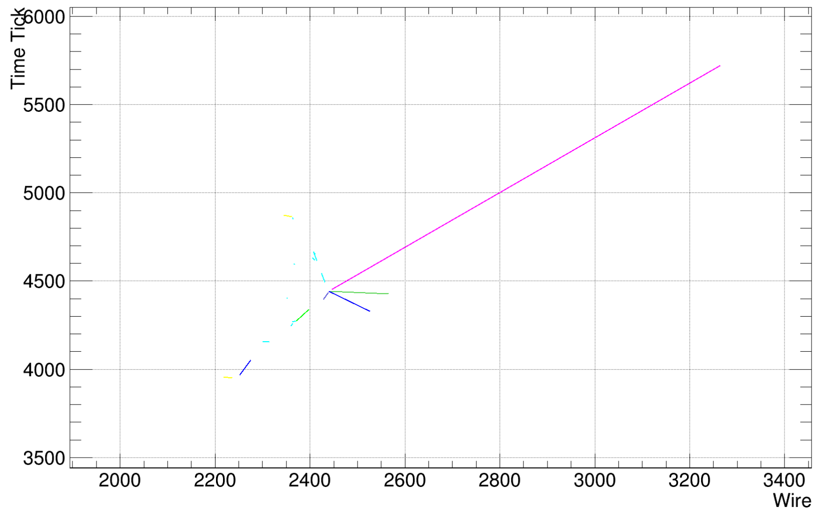

Figure 14: Y-plane view of neutrino Event that passed all cuts. The straight lines connect start and end points of 2D clusters. Zoomed in to interesting section.

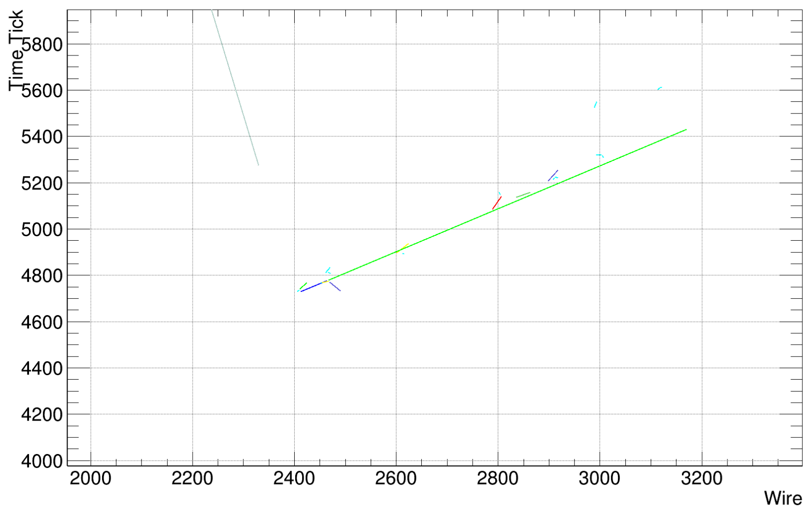

Figure 15: Y-plane view of cosmic Event that passed all cuts. The straight lines connect start and end points of 2D clusters. Zoomed in to interesting section.

our signal to background ratio. Figures 14 and 15 are neutrino and cosmic events that passed the primary and secondary cuts.

3.1.3 Final Steps

As described above, the neutrino selection on 2D clusters provides a basic and robust approach to select neutrino candidate events. Based on MC studies, the background of cosmic events can be reduced to approx. 15% of the neutrino event yield. (Note that this estimate is based on the assumption that optical and topological selection efficiencies multiply, which is not true.) We are therefore going to run this selection chain in addition to the 3D tracking approach that is described below. The efficiency of the 2D selection is lower than the efficiency of the 3D selection, but nevertheless, this is an alternate approach that is a good backup in case 3D track reconstruction does not perform well on BNB events for some reason.

3.2 Selection based on 3D tracks and vertices

3.2.1 Vertex with two tracks

The selection of neutrino candidate events is based on finding trios of a reconstructed vertex plus two tracks[6]. We loop over all reconstructed vertices and all reconstructed tracks (with a geometry cosmic tagger score < 0.4) and for each trio combination that can be formed, we calculate the following distances (illustrated in Figure 16):

- d: distance between the start points of the two tracks
- d_1: distance between vertex and start of track 1
- d_2: distance between vertex and start of track 2

Please note that the direction of the track gets flipped such that the point closest to the vertex is the start point. Note that this also means that if the same track

[6]The code to produce tables 5-7 and figures 17, 18, 19 can be found in uboonecode feature branch feature/Anne_NeutrinoIDFilter in the script uboonecode/uboone/TPCNeutrinoIDFilter/AnalysisScripts/StatisticsForPairPlusVertex.C

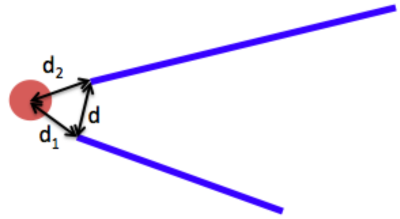

Figure 16: Sketch of the neutrino candidate topology (1 reco vertex + 2 reco tracks) and definitions of relevant distances.

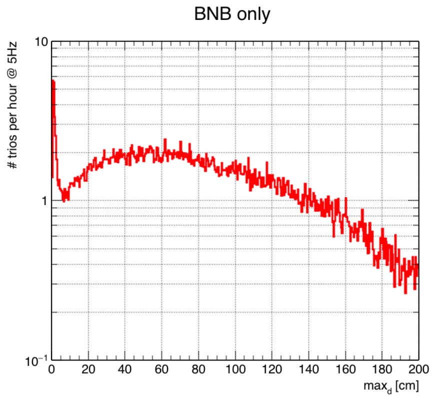

Figure 17: Distribution of $\max_d$ for all trios found in all BNB events. There are clearly two populations: the peak at small values are the trios that really belong together. The broad bump at higher values are random combinations of tracks and vertices.

is part of trio with a different reco vertex, its direction might be the other way. We do this flipping because track directionality (based on calorimetry or delta ray direction) is not yet implemented in e.g. trackkalmanhit.

We then select $\max_d = \max(d, d_1, d_2)$ as the relevant characteristic for each trio found in the event. The distribution of $\max_d$ is shown in Figure 17.

The next step is to select the best trio of each event and based on this make a decision to keep or reject an event. The best trio is the one with the smallest maximum distance within it, i.e. $min\,(\max_{d,i})$, where i loops over all trios in the event. The distribution is shown in figure 18 for BNB neutrinos and in figure 19 for cosmics. It is obvious, that $min\,(\max_{d,i})$ is much smaller for neutrino events than for cosmic events.

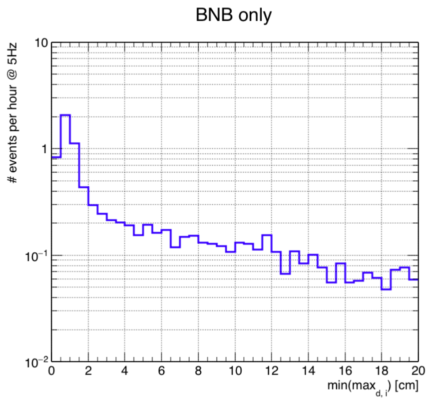

Figure 18: Distribution of min(max$_{d,i}$) for all BNB events.

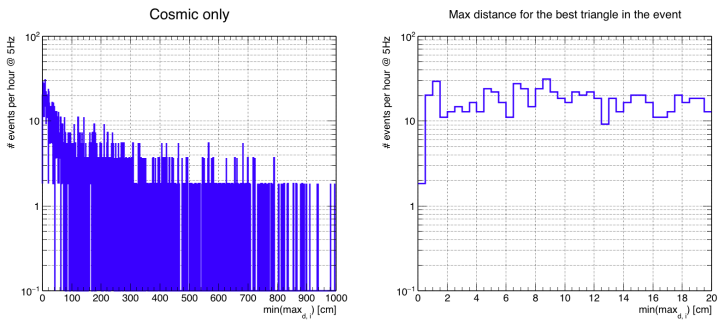

Figure 19: Distribution of min(max$_{d,i}$) for all Cosmic events. The plot on the right shows a zoom in to the first 20 cm.

Cut value in cm	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Neutrinos	0.6	2.5	3.4	3.8	4.0	4.2	4.3	4.4	4.6	4.7
Cosmics (no flash)	0	22.1	46.0	64.5	75.5	93.9	110.5	123.4	139.9	160.2
Neutrino/Cosmics	-	14.2	9.2	7.3	6.6	5.5	4.9	4.5	4.1	3.7

Table 5: Passing rates for the combination of **trackkalmanhit and cccluster vtx** as a function of the cut value chosen for $\min(\max_{d,i})$. The second line shows neutrino numbers, the third line cosmic numbers not applying the flash finding. All event numbers are normalized to events per hour assuming we are running at 5 Hz.

Note that this topology does not prevent us from finding neutrino topologies with more than two tracks. In a case with multiple tracks, the trio of the two tracks closest to the vertex will be used to make the decision. Also note that this selection does not prevent us from selecting events with a shower (or multiple showers) as long as they have two tracks (e.g. muon plus proton), which are reconstructed.

Different combinations of vertex and track reconstruction algorithms have been tested and the following combinations have been chosen:

- trackkalmanhit with cccluster, $\min(\max_{d,i}) < 3$ cm.
- trackkalmanhit with pandoraNu, $\min(\max_{d,i}) < 4.5$ cm.
- pandoraNu with cccluster, $\min(\max_{d,i}) < 5$ cm.

The cut value was chosen such that the cosmic background contamination is less than 20% based on the assumption that the flash-finding would reduce the background rate by another factor of 0.008. Since the efficiencies of optical and topological cosmic tagging are not independent, this assumption is probably too optimistic. A global efficiency will need to be determined. Tables 5 to 7 show the passing rates for neutrinos and backgrounds based on MCC6.1.

3.3 TPC selection updates

After looking at the first beam data processed with the filters, visual scanning of the passing events showed that the background contamination was larger than

Cut value in cm	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Neutrinos	0.8	2.9	4.0	4.5	4.8	5.0	5.2	5.4	5.6	5.8
Cosmics (no flash)	1.8	22.1	51.6	62.6	75.5	90.2	103.1	119.7	132.6	156.5
Neutrino/Cosmics	56.2	16.4	9.8	8.9	7.9	6.9	6.3	5.7	5.3	4.6

Table 6: Passing rates for the combination of **trackkalmanhit and pandoraNu vtx** as a function of the cut value chosen for $\min(\max_{d,i})$. The second line shows neutrino numbers, the third line cosmic numbers not applying the flash finding. All event numbers are normalized to events per hour assuming we are running at 5 Hz.

Cut value in cm	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Neutrinos	0.2	1.4	2.5	3.0	3.3	3.5	3.6	3.8	3.9	4.0
Cosmics (no flash)	1.8	12.9	33.1	49.7	51.6	55.2	57.1	58.9	70.0	73.7
Neutrino/Cosmics	12.6	13.5	9.4	7.5	8.0	7.9	8.0	8.0	6.9	6.8

Table 7: Passing rates for the combination of **pandoraNuKHit track and cccluster vtx** as a function of the cut value chosen for $\min(\max_{d,i})$. The second line shows neutrino numbers, the third line cosmic numbers not applying the flash finding. All event numbers are normalized to events per hour assuming we are running at 5 Hz.

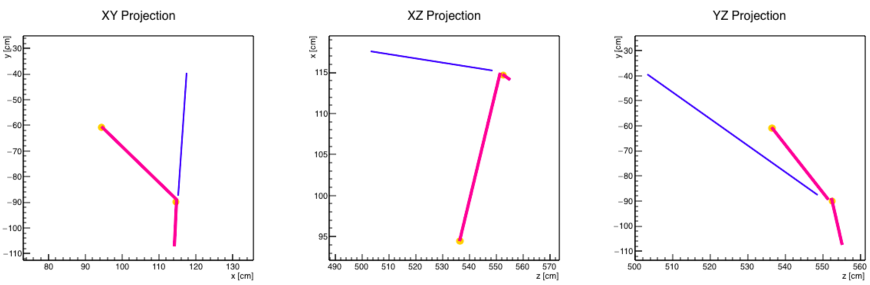

Figure 20: Projections of a BNB simulated event that passes the 3D selection criteria. The two pink tracks are the two tracks that form the trio together with the vertex they are connected to (orange triangle).

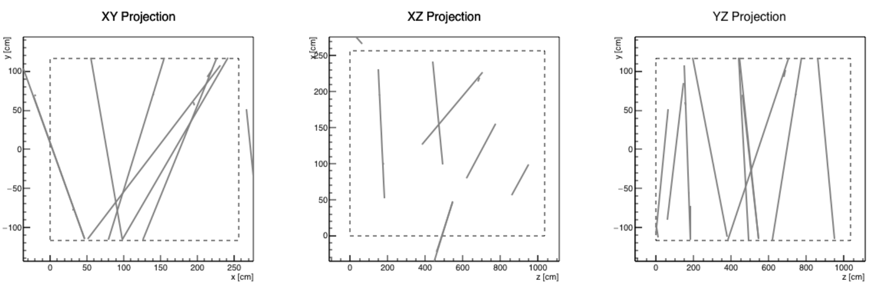

Figure 21: Projections of a cosmic only simulated event that does not pass the 3D selection criteria. The grey tracks are all tagged by the geometry cosmic tagger. There is only a single tiny contained track that can't fulfill the selection.

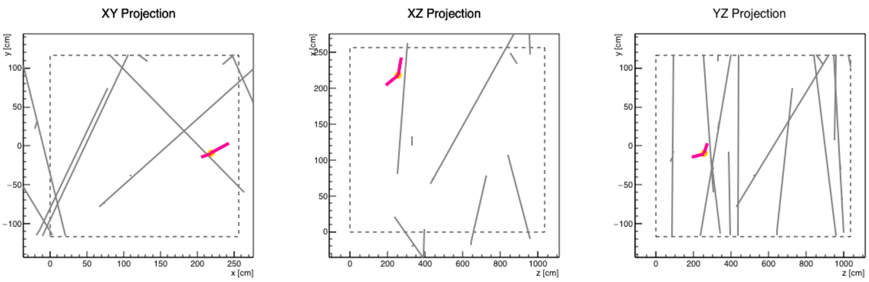

Figure 22: Projections of a cosmic only event that passes the 3D selection criteria and creates a fake signal. The two pink tracks are the two tracks that form the trio together with the vertex they are connected to (orange triangle).

expected. Most of this can be attributed to the reconstruction performance to be not as high on data than on simulation. Therefore, additional cuts have been developed based on visual studies, in order to increase the signal fraction in the events selected by the filter. These cuts are added on top of the filters described above and just further reduce the event number, but don't add any extra events.

3.3.1 Changes in the 2D filter

A main background observed in the 2D filter were Michel events, where the muon and the electron formed two connected clusters. In order to reject such events, it is required that the start charge of the long cluster (muon candidate) is smaller than the end charge of the cluster. This is because the muon does have a larger ionization loss at the end.

3.3.2 Changes in the 3D filter

Changes in the 3D filter are made to the direction of the reconstructed tracks. It has been observed that cosmic tracks do accidentally originate/end from the same point, which can fake a signal. However, cosmic tracks are mostly vertical. Therefore, it is required that the angle of the longer track in the pair wrt the z-axis has a cosine of larger 0.85. In addition, it is required that the longer of the two tracks is larger than 10 cm.

3.4 TPC selection conclusion

For the inital selection of neutrino candidate events, we ran the following filters in parallel:

- 2D cluster selection as described in subsection 3.1
- 3D track and vertex selection for three different combinations of track reconstructions and vertex algorithms as described in subsection 3.2.1: trackkalmanhit + ccluster/linecluster vtx, pandoraNuKHit + ccluster/-linecluster vtx, trackkalmanhit + pandoraNu vtx. Cut values for minimum distances are listed above.

This gives four streams that output neutrino candidate events. We do expect a large overlap between these.

4 Data processing plans and results

4.1 Strategy

We have processed the data using a series of LArSoft filter modules, to gradually reduce the number of candidate neutrino interaction events.

4.1.1 Filter 1: Loose Flash Filter

We pass events through a filter that looks at flashes reconstructed during the unbiased PMT readout window that includes the beam spill. This window is 10 μs long, and early timing indications from the RWM (summarized in Section 2.4.1) showed this region was very likely to contain the beam spill period.

Based on the work shown in Section 2, we expect about 5% of events containing only cosmic rays to pass this requirement for a large flash in this 10 μs window. Assuming a 5 Hz BNB rate, this would yield 900 events per hour.

From the calculation in Section 1.2, we expect around 27 neutrino interactions per hour. We expect 100% to pass the flash-timing cut, while 82% (from Section 2.2) of these events will pass the 50 PE threshold, leaving about 22 neutrino interactions per hour. This ignores dirt interactions or other beam-spill-related phenomena, and relies on an efficiency measurement from lower-PE-yield -128-kV MC samples.

At this stage, the sample is expected to be roughly 2% neutrino interaction, and 98% cosmics.

4.1.2 Filter 2: TPC Reco Filter

Events that pass the loose flash filter may then be passed through the TPC reconstruction chain in order to apply the selection on neutrino interaction topologies described in Section 3. One of the best performing selections is the 3D selection using the TrackKalmanHit tracking algorithm with PandoraNu vertexing. Performance is listed in Table 6. If we take the 3 cm distance cut, then roughly 5 neutrino interactions survive per hour. Based on the reported number of 90.2 cosmic events per hour passing those cuts, without flash-filtering, that is an efficiency for cosmics of $90.2 \times \frac{1}{(5\text{Hz})(3600\text{s})} = 0.5\%$. Thus, if 900 cosmic events pass the first level of flash filtering each hour, then about 4.5 cosmic ray events per hour survive the addition of this TPC reconstruction filter. With a total selection of approximately 10 events per hour, this filter can provide a scannable set of data.

Events that pass this filter may be used to cross-check that the algorithms are working properly on data. Looking in the sideband region where the distance cut is less stringent would yield a higher number of cosmic rays relative to neutrino interactions. As mentioned in Section 3.4, more complicated cuts could increase the overall efficiency without sacrificing purity.

After running through a TPC-reconstruction-based filter, we expect the event sample to be about 50% neutrino interactions, and 50% cosmic-only events.

4.1.3 Filter 3: Tight Flash Filter

With data collected over the first 24 hours, the beam timing can be measured more precisely following the method described in Section 2.4. Assuming that after 8-24 hours of flash data (passing the loose flash timing filter) we can measure the beam spill to within 1.6 μs total width, then the cosmics events that have passed the filters up to this point will be reduced by a factor of ten. The neutrino events should be unaffected. Thus, the final selection will yield about 5 neutrino events per hour, but about only 1 cosmic event per hour passing all requirements. This will be a high-purity neutrino sample: roughly 80% neutrino interactions, compared to 20% cosmics events. From the first 24 hours of data then, we expect about 136 total neutrino interaction candidate events, which we expect to contain 120 neutrino interaction events, and 16 cosmics events.

4.2 Results

The results from the studies of flash timing have been shown in Section 2.4.2. From Figure 9, we can see that there is a 15% excess in events in time with the beam spill, which matches the expected excess (see Figure 8). Based on these studies, we can easily narrow into a region associated with the beam spill between 3 and 5 μs after the trigger.

Table 8 shows the event passing rates for a combination of the optical and topological filters on experimental off-beam data. Note that the modification to the 3D filter improves the background rejection by a large degree. For the 2D selection, the passing rate is only a factor of two times higher than the naive expectation from simulation where we assumed completely uncorrelated topological and optical filters.

We have two methods available for determining background cosmic-ray-event contributions to our neutrino ID selection. First, we can run the filter selection on backgrounds from off-beam data, and determine a cosmic misidentification rate (per event) for passing our neutrino selection. Second, we can run the TPC

	Number of events
Total	30862
Flash in 10(2) μs timing window	1373 (301)
After original 2D selection	88 (17)
After modified 2D selection	52 (7)
After original 3D selection	11 (1)
After modified 3D selection	0 (0)

Table 8: Event counts the topological filters from experimental off-beam cosmic data for different time windows. The 2D and 3D selections are independent (that is, the 3D selection is not re quired to pass the 2D selection)

reconstruction and topological filters run on a wider time range of the data than selected with the narrow beam-spill window, and similarly we can obtain estimates of the off-beam (cosmic) background expectation to our final filter. Our strategy is to run the TPC filter selections on events that have flashes that pass the 50 PE threshold and have reconstructed flash times between 2 and 6 μs after the trigger on datasets without and with beam, which allows splitting of the samples into an "on-spill" (between 3 and 5 μs after the trigger) and "off-spill" (other times) time selection. In addition, we run over data in which there was no beam.

In Table 9, we show the number of events that pass the 2D and 3D selections in a set of runs that contain no beam (cosmics only). In a total of 21616 total original events that pass our loose optical selection (again, with reconstructed flash time between 0 and 10 μs after the trigger), a total of 4 events pass our final 3D selection and are inside a tighter timing window between 2 and 6 μs after the trigger, giving as a very low expected rate of cosmic ray events in our neutrino sample. Furthermore, while it is low in statistics, the flashes appear to occur with a flat distribution in time, as is expected from random cosmic rays. The 2D selection also shows a significant cosmic-ray rejection rate, but overall it sees a higher rate of cosmic-rays that survive the cuts, and there is some tension on the flat assumption of the timing selection.

From the results of the off-beam data studies, we expect the likelihood a cosmic ray event is ID'ed as a neutrino is $\frac{4}{21616} = 0.02\%$ for the 3D selection,

	N_{ev}	N_{ev}, 3D selection		N_{ev}, 2D selection	
Run Number	[0 μs, 10 μs]	[2 μs, 3 μs] or [5 μs, 6 μs]	[3 μs, 5 μs]	[2 μs, 3 μs] or [5 μs, 6 μs]	[3 μs, 5 μs]
3321	1295	1	0	8	8
3322	1333	0	0	12	7
3327	2981	1	1	28	25
3329	1886	0	0	19	24
3349	4856	0	0	48	39
3353	2839	0	1	11	27
3354	462	0	0	5	5
3364	855	0	0	1	8
3366	537	0	0	6	9
3383	928	0	0	6	9
3385	1790	0	0	14	15
3386	1854	0	0	9	18
Total	21616	2	2	167	194

Table 9: Passing rates for the topological filters from experimental **off-beam** data for different time windows. We compare a wider and narrow time window to check that cosmic background rates do not appear to differ based on timing selections.

and $\frac{361}{21616} = 1.67\%$ for the 2D selection

Table 10 shows a similar description of data but on a set of runs from beam data. The total number of events after a loose optical filter is roughly twice that from our off-beam sample: 44355 total events. Assuming a flat time distribution, we expect half of those events to occur outside the on-spill time region, and from our off-beam data we would then expect $0.02\% \times \frac{44355}{2} = 4.1$ events to appear in the off-spill region for the 3D filter, and $1.67\% \times \frac{44355}{2} = 370$ events to appear in the off-spill region for the 2D selection. In fact, we observe 5 and 401 events, respectively, in agreement with these predictions, and bolstering our background estimates.

We see more events in the on-spill regions from both selections. For the 3D selection, 18 events pass all cuts, which is significantly more than the predicted 4-5 events based on all background regions. Assuming all non-cosmic contributions are from neutrinos, the neutrino interactions make up roughly 70% of that sample (we do not do a sophisticated error analysis here, and simply present

	N_{ev}	N_{ev}, 3D selection		N_{ev}, 2D selection	
Run Number	[0 μs, 10 μs]	[2 μs, 3 μs] or [5 μs, 6 μs]	[3 μs, 5 μs]	[2 μs, 3 μs] or [5 μs, 6 μs]	[3 μs, 5 μs]
3455	3869	0	3	33	27
3456	293	0	0	3	2
3457	4062	0	1	38	54
3468	6278	0	1	61	68
3469	6426	0	4	54	61
3470	3487	1	2	31	45
3471	5148	1	0	50	57
3472	5511	2	2	44	59
3475	2483	1	0	22	25
3476	3754	0	0	40	34
3493	2232	0	5	15	32
3494	812	0	0	10	8
Total	44355	5	18	401	463

Table 10: Passing rates for the topological filters from experimental **beam** data for different time windows. We compare a wider and narrow time window to get a sense of cosmic background rates.

these rough numbers). For the 2D filter, this fraction is roughly 15%, though with an expected higher efficiency for selection. The 3D filter performs better, largely by being able to impose true containment on the reconstructed interactions; the 2D filter is blind to tracks that enter and/or exit from the top or bottom of the TPC.

4.3 Processing Conclusions

As can be seen from Table 10, there is strong evidence of neutrino interactions in our final selection. While in the 2D filter selection the overall purity is low, there is a much higher purity in the 3D filter selection that produces a high-confidence sample of neutrino interaction candidate events.

5 Additional methods considered / Future improvements

5.1 Flash Matching

Flashes that are reconstructed will have light on multiple PMTs, but not all PMTs. Using information about the location of light deposits, and the size of each light deposit, it is possible to estimate where in the tank the flash originated. Of course, the flash will come from an extended source, but the centre-of-charge should correspond roughly to the reconstructed flash position. Flash matching is not currently used to select neutrino interactions, however in the future it is expected to be a valuable resource for increasing the purity and efficiency of neutrino event selections.

5.2 π^0 Topological Filter

Using 2D cluster and 3D shower reconstruction, it is possible to devise a selection for events that contain two electromagnetics showers consistent with coming from the decay of a neutral pion. This selection could be powerful in opening up more neutral current neutrino interactions into our first event selection, as well as provide a different, interesting topology to display in our first event set. Howeber, the π^0 stream is not yet ready for implementation and we are not planning to have it running in the first couple of days. A dedicated π^0 filter will be further developed and added to the proposal later on. Some first ideas for this can be found in DocDB 4770.

5.3 Data runs used for this analysis

- **Off-beam:** 3321, 3322, 3327, 3329, 3349, 3353, 3354, 3364, 3366, 3383, 3385, 3386

- **On-beam:** 3455, 3456, 3457, 3468, 3469, 3470, 3471, 3472, 3475, 3476, 3493, 3494

5.4 Events passing the neutrino ID filter selection

The first filtering level is to filter events within a time window from 2μs to 6μs, and which are passing either the modified 2D or the modified 3D filter. The events passing these filters can be found in files located in `/pnfs/uboone/scratch/users/aschu/data-reprocess/v04_26_03_01`.

These files have been further merged and subdivided by filter and time window. The base directory is `/uboone/data/users/aschu/`. On-Beam runs can be found within this directory in:

- Passing 2μs to 6μs window and modified 2D filter: `reprocessNuID/run*-2Dmod-4us.root`
- Passing 3μs to 5μs window and modified 2D filter: `reprocessNuID/run*-2Dmod-2us.root`
- Passing 2μs to 6μs window and modified 3D filter: `reprocessNuID/run*-2Dmod-4us.root`
- Passing 3μs to 5μs window and modified 3D filter: `reprocessNuID/run*-2Dmod-2us.root`

Off-Beam runs can be found in:

- Passing 2μs to 6μs window and modified 2D filter: `offBeamNuID/run*-2Dmod-4us.root`
- Passing 3μs to 5μs window and modified 2D filter: `offBeamNuID/run*-2Dmod-2us.root`
- Passing 2μs to 6μs window and modified 3D filter: `offBeamNuID/run*-2Dmod-4us.root`
- Passing 3μs to 5μs window and modified 3D filter: `offBeamNuID/run*-2Dmod-2us.root`

The list of events can be found in table 11.

References

[1] Sarah Lockwitz, *DocDB3413*, April 25, 2014.

Run	Subrun	Event
3455	101	5063
3455	541	27080
3455	614	30716
3457	708	35441
3468	796	39809
3469	132	6603
3469	1594	14205
3469	574	28734
3469	1064	53223
3470	131	6593
3470	1287	64351
3472	1669	17918
3472	881	44079
3493	95	4782
3493	201	10051
3493	241	12092
3493	794	39736
3493	821	41075

Table 11: List of events within the $3\mu s$ to $5\mu s$ time window passing the modified 3D selection for runs 3455 to 3494.

[2] H. Simgen, G. Zuzel, *Radon Emanation Measurements*, http://www.mpi-hd.mpg.de/gerda/lngs07/lngs07_slides/zuzel_gerda_nov07.pdf.

[3] F. Cavanna et al., *Radon emanation measurements at LNGS*, internal communication.

[4] D. Kaleko, *PMT Triggering and Readout for the MicroBooNE Experiment*, Proceedings from the LIDINE conference at Fermi National Accelerator Laboratory, June 2013.