Study of muon neutrino interactions in MicroBooNE

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Abstract

This report describes study of muon neutrino interactions in the MicroBooNE detector, with focus set on the optical information from the photomultiplier tubes. MicroBooNE uses Liquid Argon Time Projection Chamber to provide 3-dimensional reconstruction of charged particles tracks in the detector volume. Event reconstruction is based on two signals: prompt scintillation light recorded by photomultiplier tubes and ionization current observed on three wire planes. MicroBooNE is located on the Booster Neutrino Beam line, 470 m from the target. Neutrinos are delivered in spills of 1.6 μs each. The prompt optical information is crucial in determining weather the interaction occurs in-time with the beam spill and may be induced by a beam neutrino or out-of-time and therefore is not of interest. Two methods of storing the optical information and using it as an event selection requirement are compared. Replacement of the currently used flash method corresponding to grouping photomultipliers in clusters with pure optical hits summed over all photomultipliers is suggested. The front porch veto, excluding events with optical activity detected shortly before the beam spill window, is found to not be a good tool to reject the cosmic events. Matching of flashes measured in the photomultiplier tubes with the objects detected in the time projection chamber is studied and possibilities of rejecting cosmic events based on the output variables from the matching algorithm are presented.

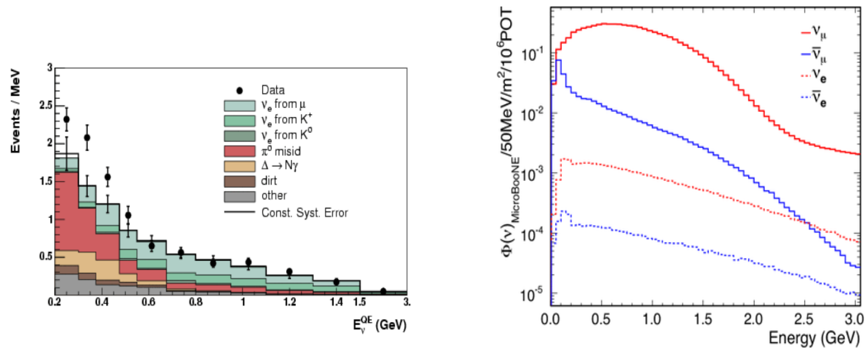
Contents

1 Introduction

MicroBooNE is a Liquid Argon Time Projection Chamber (LArTPC) located at Fermilab, on Booster Neutrino Beam line, 470 m downstream from the neutrino production target. The experiment was designed to resolve the low energy neutrino excess observed by MiniBooNE (Fig. 1a) and perform precise cross section measurements in argon. The experiment is part of the Short Baseline Neutrino program, currently being constructed in Fermilab, aiming to study neutrino oscillations and search for the sterile neutrinos.

The TPC is placed in a cryostat, on the ground level. Therefore, apart from neutrinos coming from BNB, the experiment suffers high cosmic background. Precise selection of neutrino induced events is essential for studies of neutrino interactions in MicroBooNE.

This study focuses on muon neutrinos, produced primarily from pion decays, which are the main constituent of the Booster Neutrino Beam (Fig. 1b). Muon neutrino interactions need to be distinguished from both cosmic induced events and other neutrino interactions. Selection paths used by the MicroBooNE collaboration were studied, with focus set on the optical information cuts.



(a) MiniBooNE low energy excess in neutrino mode [1].

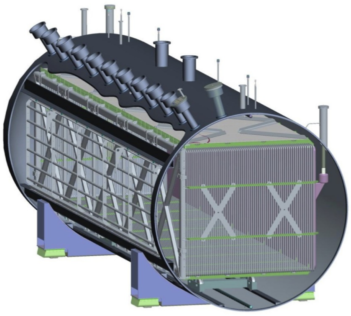
(b) The Booster Neutrino Beam flux at MicroBooNE [2].

Figure 1

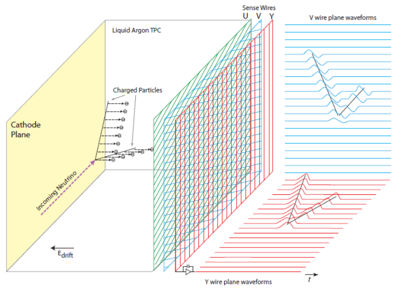
2 Neutrino detection in MicroBooNE

Booster Neutrino Beam is created by impacting accelerated up to 8 GeV protons on a beryllium target. The spill length is 1.6 μs with $\sim 5 \times 10^{12}$ protons per spill delivered on target.

The LArTPC detects neutrino interactions using three wire planes and array of 32 photomultiplier tubes (PMT), located inside the cryostat (Fig. 2a). Charged particles traversing the detector leave trails of ionization electrons and create prompt vacuum ultraviolet scintillation photons. The ionization trails are transported under the influence of electric field in the detector volume. The high voltage is applied onto a cathode plane and gradually steps down in magnitude across a field cage towards the anode plane. Both anode and cathode planes are parallel to the BNB direction. Three planes of sense wires, with predefined bias voltage, sense signals induced by the ionization electrons drifting towards them. The trajectory of charged particle is reconstructed using position of the waveforms on the wire planes and the drift time. The scintillation photons are detected by the array of PMT facing into the detector volume. Light collection system provides signals that can establish the time of interaction and enables to distinguish detector activity that is in-time with the beam and possibly originates with beam neutrinos from the out-of-time activity.



(a) The TPC inside the cryostat: the cathode plane is on the right, the wire planes and PMT array are on the left.



(b) Operational principle of the MicroBooNE LArTPC.

Figure 2

3 Event rates in MicroBooNE

Neutrino interactions are mediated by either charged or neutral currents. Different channels of interactions are defined based on the final state particles that emerge from the interaction:

- quasi elastic scattering (QE)
- resonant pion production (RES)
- deep inelastic scattering (DIS)
- coherent pion production (COH)
- meson exchange current (MEC)

Latest release of MicroBooNE Monte Carlo simulation, MCC8.1 is the first version that includes meson exchange current (MEC) interactions. The event rates for specific interaction channels were studied for the MCC8.1 simulation, and compared with previously analyzed MCC6. The rates are shown in Tab. 1. For both simulation releases the numbers of events are scaled to 6.6e20 POT, corresponding to 3 years of data taking.

The main difference in the overall number of events is due to adding MEC interactions, which constitute $\sim$20% of all events. Discrepancies in resonant and deep inelastic interactions come from the difference in used definitions for those channels: in MCC6 analysis the discrimination between RES and DIS is based on a cut on hadronic invariant mass W - for RES: $W < 2$ GeV and DIS:

Table 1: Expected event rates of BNB neutrinos in MicroBooNE for different interaction channels for an 87 ton active volume and 6.6e20 POT simulated with MCC6 and MCC8.1.

MCC6 [2]

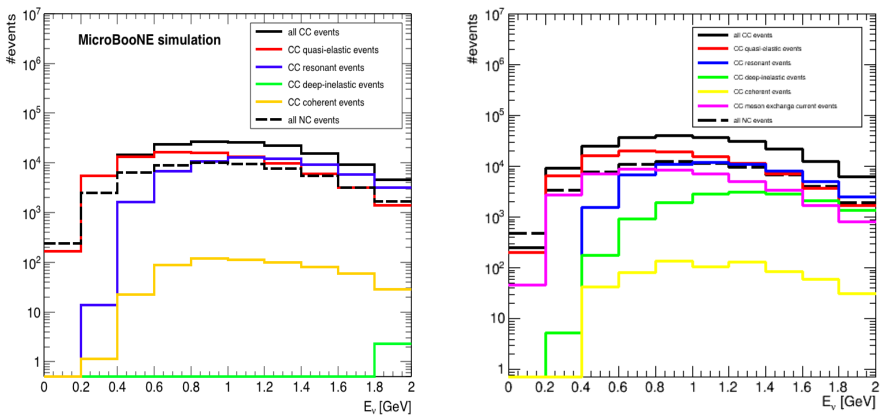
	numu	numubar	nue	nuebar
CC Total	173302	1407	1469	36
CC - QE	95296	773	729	17
CC - RES	75657	604	702	18
CC - DIS	1607	1.3	29	0.5
RES+DIS	77264	605.3	731	18.5
CC - COH	740	29	8.5	0.7
NC Total	64661	1002	502	17
NC - QE	35951	633	254	7.0
NC - RES	27665	358	236	9.4
NC - DIS	519	1.3	8.8	0.2
RES+DIS	28184	359.3	244.8	9.6
NC - COH	525	10	3.2	0.6

MCC8.1

	numu	numubar	nue	nuebar
CC Total	234941	1958	1997	47
CC - QE	104235	984	762	10
CC - RES	62741	439	614	26
CC - DIS	20484	120	251	5
RES+DIS	83225	559	865	31
CC - COH	749	16	10	0
CC - MEC	46732	399	360	5
NC Total	73449	1073	546	24
NC - QE	34622	590	251	16
NC - RES	23727	285	162	3
NC - DIS	6823	89	63	5
RES+DIS	30550	274	225	8
NC - COH	590	18	5	0
NC - MEC	7661	91	65	0

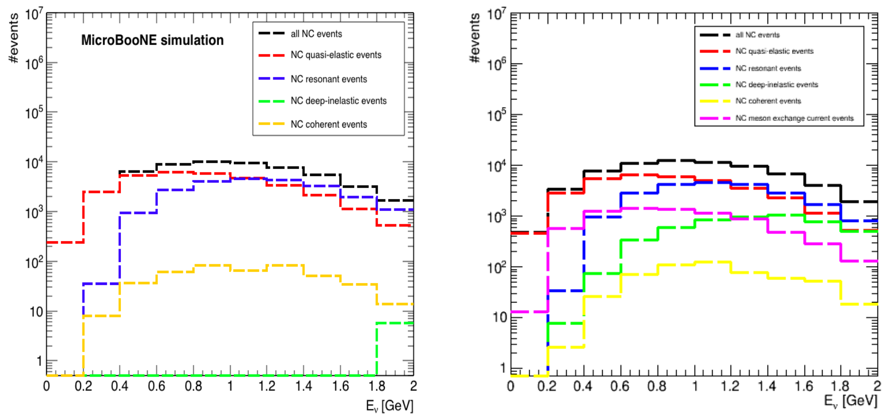
$W > 2$ GeV, whereas in MCC8.1 the Genie Truth information is used. Therefore, a migration between RES and DIS events can be observed. For easier comparison the sum of RES and DIS events, which should not change significantly, was added to the table.

The expected energy distributions for specific channels were plotted in Fig. 3 and 4 for both MCC6 and MCC8.1 simulations regarding both charged current and neutral current interactions.



(a) (b)

Figure 3: Energy distribution of BNB muon neutrino charged current event rates in MicroBooNE for different interaction channels for an 87 ton active volume and 6.6e20 POT, simulated with MCC6 (a) and MCC8.1 (b).



(a) (b)

Figure 4: Energy distribution of BNB muon neutrino neutral current event rates in MicroBooNE for different interaction channels for an 87 ton active volume and 6.6e20 POT simulated with MCC6 (a) and MCC8.1 (b).

4 Study of PMT cuts

Precise measurement of muon neutrino cross-sections requires very efficient selection of events. Two selection paths are used in order to distinguish muon neutrino interactions from other events (including electron neutrino interactions and cosmic-induced events). The requirements of the selection paths are shown in Fig. 5. Due to different cuts, the efficiencies are 12% and 30%, and purities 55% and 65% for selection I and selection II, respectively.

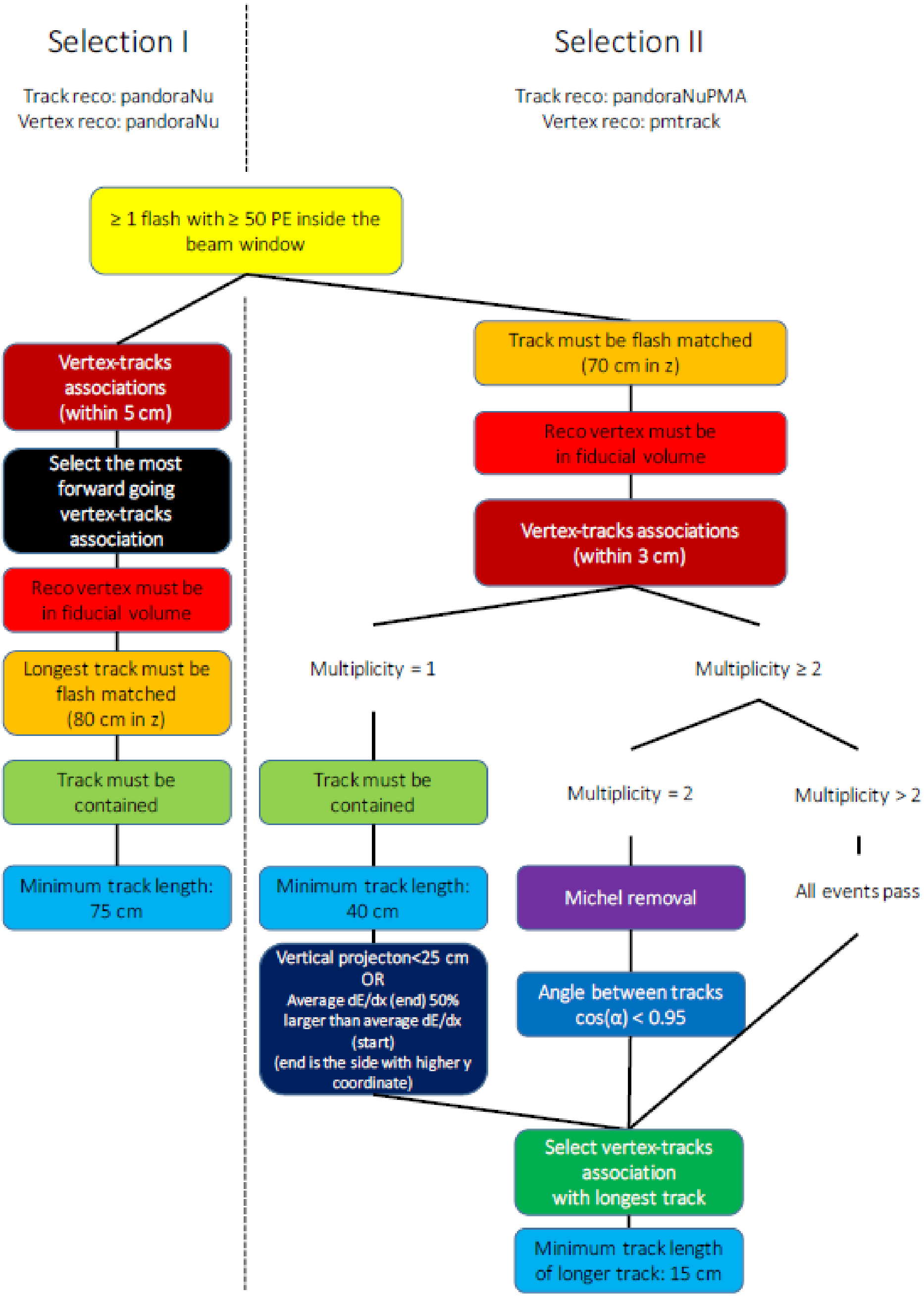


Figure 5: Event selection diagram for selections I and II, illustrating the different paths. Both selections start with the exact same cut requiring a flash in the beam window using the same flash reconstruction. Boxes in the same color symbolize similar cuts (not necessarily the same cut values) for different paths [4].

Both paths start with a requirement of having at least one flash with at least 50 photoelectrons (PE) deposited in the PMTs inside the beam spill window. This requirement gives efficiency of 95.8% and cosmic rejection of 99%, where signal events are defined as muon neutrino charged current interactions inside the fiducial volume (FV - TPC active volume reduced by 10 cm from both sides along x, z directions and 20 cm along y direction). Efficiency and background rejection are defined as:

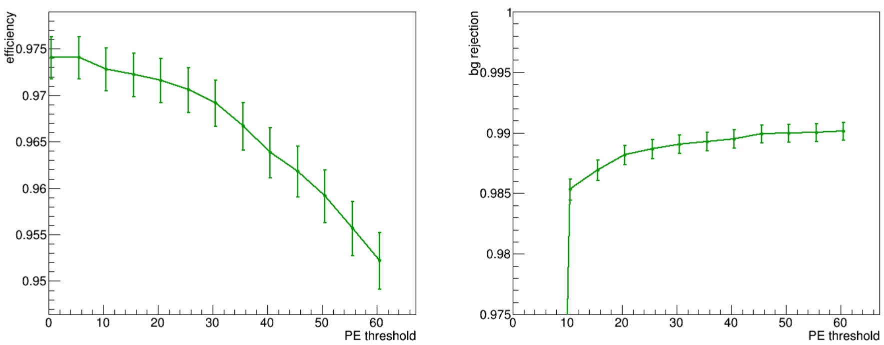
$$\text{Efficiency} = \frac{\#\nu_\mu\text{CC in FV with PE} \geq \text{ threshold PE and in the beam spill window}}{\#\nu_\mu\text{CC in FV}} \quad (1)$$

$$\text{Bg Rejection} = 1 - \frac{\#\text{events with PE} \geq \text{threshold PE and in the beam spill window}}{\#\text{all events}} \quad (2)$$

Possibilities of improving performance of the first selection requirement were studied using two approaches. First one was based on Optical Flashes, which are being used currently. The threshold value of photoelectrons defining signal was optimized. Another approach followed idea from the MicroBooNE Deep Learning Working Group to use Optical Hits instead of Flashes. Optical Hits provide pure information from the PMTs and do not need any grouping algorithms. However, a way of defining signal from hits had to be defined.

4.1 Optical Flashes

Optimization of flash requirement was studied by varying the value of threshold PE, above which events are selected. Efficiency of signal selection and rejection of cosmic induced events were checked at different values of threshold PE, Fig. 6a and 6b. For the efficiency study a sample of simulated neutrino and cosmic events was used (`prodgenie_bnb_nu_cosmic_uboone`), and for rejection study Corsika simulation (`prodcosmics_corsika_cmc_uboone`) with cosmic events only. The OpFlash algorithm of grouping information from PMTs to create flashes was used.



(a) (b)

Figure 6: Efficiency of signal selection (a) and cosmic background rejection (b) as functions of flash threshold PE.

The current 50 PE threshold provides high cosmic rejection. It can be noticed, that changing the threshold value between 40 and 60 PE does not cause

Table 2: Comparison of efficiency and cosmic rejection for flash requirement of 40 and 50 PE.

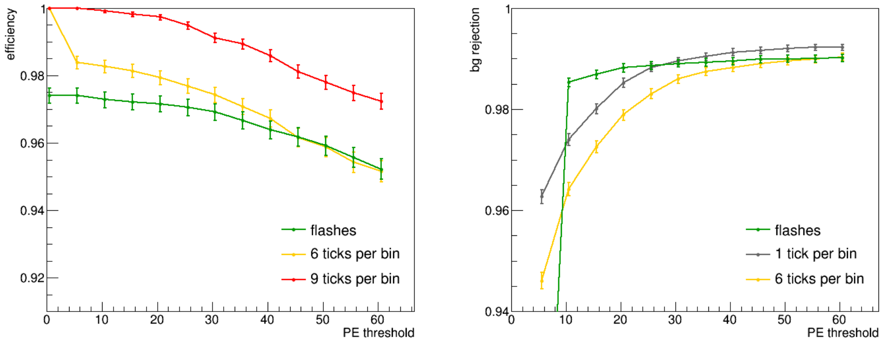
	Efficiency	Cosmic rejection
OpFlash $\geq$ 50 PE	95.8%	99.0%
OpFlash $\geq$ 40 PE	96.4%	98.9%

significant changes in cosmic rejection, the distribution is almost flat in that region. On the contrary, efficiency of selection is higher for lower values of threshold. Therefore, the performance of the flash requirement can be improved with the flash PE threshold value 40, which provides higher efficiency with only a slight decrease in cosmic rejection, as shown in Tab. 2.

4.2 Optical Hits

Optical Hits (OpHits) represent another method of storing optical information from the PMTs. OpHits correspond to single PMT, not groups of them as in OpFlashes. OpHits represent recorded waveforms, which are acquired with a time resolution of 15.625 ns. The idea of using pure optical information from OpHits instead of OpFlashes was introduced by the Deep Learning Group [3]. In this study, the proposed method was reproduced for study of ν_μ CC interactions.

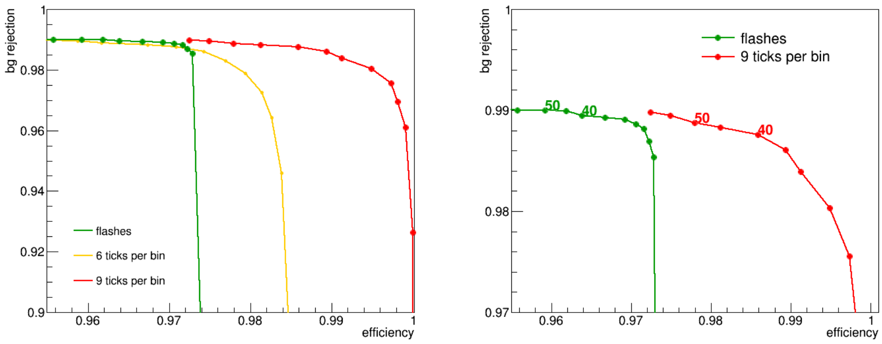
Changing the algorithm from OpFlashes to OpHits means redefining the signal requirement. Provided the OpHit information for each time tick, one can create (in given region of time interest, here: inside the beam spill window) new bins consisting of n time ticks. For each new bin created that way, the OpHits from all PMTs are summed and constitute a total PE of the event. Then the threshold PE is defined in a way that each event where (in at least one bin) the number of PEs exceeds the threshold value - the event is selected. Therefore there are two parameters that can be optimized: number of ticks per bin and threshold PE. Different choices of binning are plotted in Fig. 7a and 7b, showing efficiency and background rejection as functions of threshold PE.



(a) (b)

Figure 7: Efficiency of selecting ν_μ CC in FV events (a) and cosmic background rejection (b) as functions of OpHit threshold PE, for different binning settings. Corresponding curves for OpFlashes (green) are shown for comparison.

The green curve corresponding to flashes is showed for comparison with current requirement. The efficiency of selecting signal events in Fig. 7a can be increased by switching from OpFlashes to OpHits. The wider the binning (the more ticks per bin), the higher the efficiency is. However, the behavior of bins with more than 9 ticks per bin remains similar. Looking at the efficiency plot, replacement of OpFlashes with OpHits enables to select more events even with lower PE threshold. Comparing it to the cosmic rejection curves, Fig. 7b, currently used requirement provides one of best rejections. Better performance can be seen only with single-tick binning. For easier comparison, the ROC curves of the proposed methods are shown in Fig. 8. The 9-tick binning provides the best results: keeping the threshold PE at level of 50 retains similar cosmic rejection and provides higher efficiency. Considering that the PMT requirement is the first cut in both selection paths, the signal efficiency is of highest importance. Therefore, lowering the signal threshold PE to 40 is suggested to lower the background rejection from 99% to 98.8% but increase the signal efficiency from 95.8% to 98.6%.



(a) (b)

Figure 8: Background rejection as a function of efficiency for PMT cuts based on the OpFlash and OpHit methods. Points correspond to certain PE threshold values. In (b) the comparison of best tunings is presented: OpHits 9-tick binning and OpFlashes, the 40 and 50 PE threshold values are marked.

4.3 Comparison

Possibility of replacing current flash requirement with optical information cut was studied in deep to ensure that the loss in signal events is minimal and well understood. In the studied MC sample the overlap in events passing both selection cuts is presented in Fig. 9. Vast majority of events passing the 50 PE flash requirement also fulfills the OpHit requirement, as the threshold value is lowered to 40 PE. Overall, the redefinition of signal events results in gain of 138 events. However, 15 events that pass the previous requirement are lost.

Those signal events were investigated in the event display and a similar pattern was observed for most of them: optical activity starts in the end of beam spill window and in the end of the detector (range 600-1000 m along the z direction). The flashes reconstructed in those events are wide and only slightly exceed the 50 PE threshold. Therefore, those events seem to not be clean signatures of neutrino events, which usually correspond to sharp and high in PE flash, and can be neglected. Optical information from the event display for examples of events passing only OpFlash and both OpFlash and OpHit cuts are shown in Fig. 10.

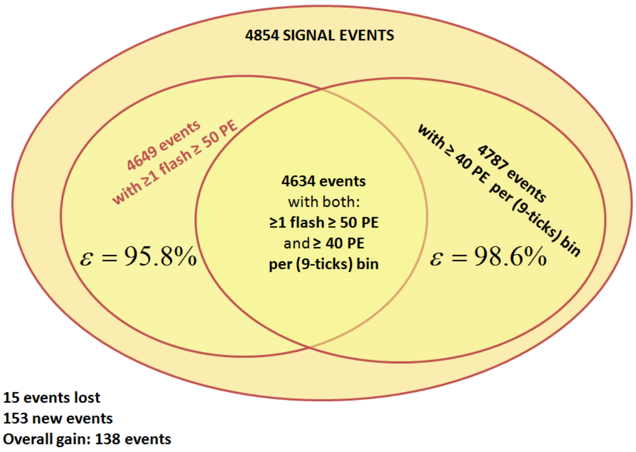
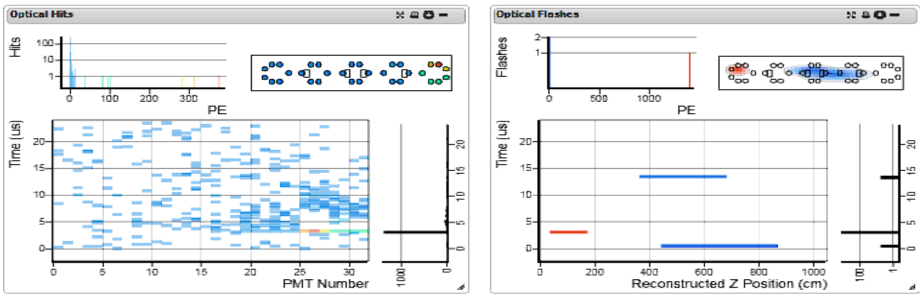
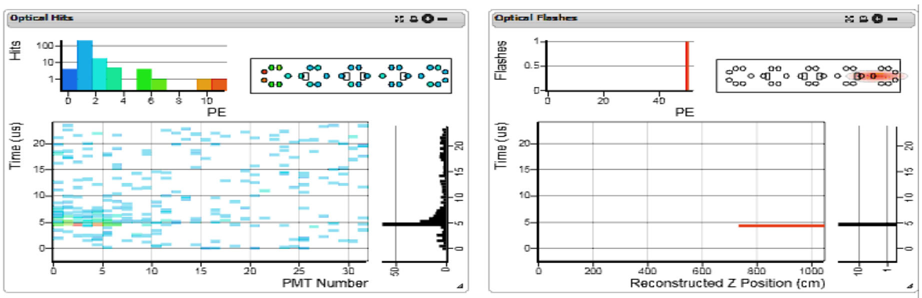


Figure 9: Overlap of signal events passing OpFlash 50 PE and OpHit 40 PE requirements (chart not to scale).



(a)

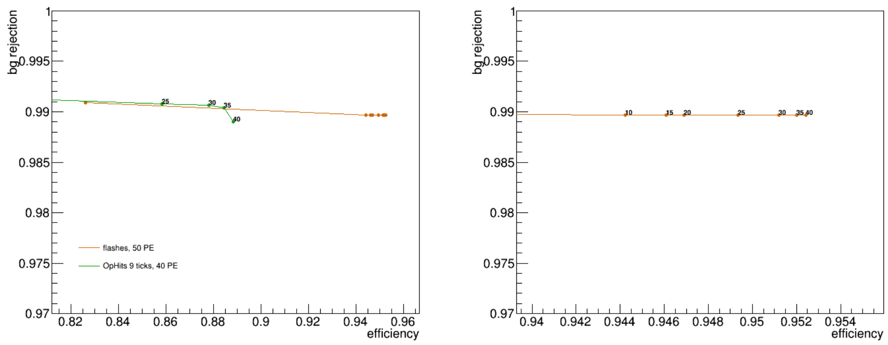


(b)

Figure 10: Optical information from event display for event 1_8063_403125 (a) passing both OpFlash and OpHit requirement and event 1_5836_291764 (b) passing only the OpFlash requirement.

4.4 Front porch veto

MicroBooNE suffers high cosmic background, therefore many approaches to exclude cosmic events are used. Introducing a front porch veto is an approach suggested by the Deep Learning Group. It is based on excluding events with light deposited in the PMTs in the pre-spill window (2 μs before the beam-spill window: 1.2 - 3.2 μs). This requirement aims to reject events where scintillation light coming from cosmic-induced events occurring before the beam spill overlaps with the beam spill window and therefore fakes neutrino signal. The idea was checked using OpFlashes and OpHits with previously chosen tuning of 9 time ticks and 40 PE as threshold value inside the beam spill window. The tuning of signal definition in the front porch veto was being studied for different PE threshold values. The ROC curves in Fig. 11 show the obtained results. Introducing the veto does not increase the level of background rejection, the distribution remains flat for multiple choices of threshold. Moreover, the overall signal selection efficiency drops and (with best tuning) reaches only 89% for flashes and 95.2% for optical hits. Therefore, the front porch veto is not powerful in excluding cosmic events.



(a) (b)

Figure 11: Background rejection as a function of efficiency for the PMT cuts with OpHits and OpFlashes, with introduced front porch veto cut. The points correspond to threshold PE above which events occurring in pre-spill window are rejected. In (b) the efficiency range of 94% to 95.5% was zoomed in.

5 Flash - TPCObject matching

After applying any of the PMT precuts, the following step in the event selection includes matching of the reconstructed flash with objects detected in the TPC. Reconstructed information from TPC (including tracks, showers, vertices) is stored as TPCObjects. For each object the hypothesis of a flash is constructed and compared with the measured flash. The best match is chosen using the likelihood method:

$$-\ln L(x) = -\sum_{i=0}^{N} \frac{(H_i(x))^{O_i} e^{-H_i(x)}}{O_i!} \quad (3)$$

where $H_i(x)$ is the photoelectron hypothesis for PMT i and O_i is the measured PE for PMT i.The matching algorithm returns a score value which corresponds to $1/-\ln L(x_{\texttt{best}})$. TPCObjects in MicroBooNE simulation have three different origins:

- neutrino - objects originating with neutrino interaction
- mixed - objects containing both neutrino induced particles and background
- other - objects with cosmic and other background events.

The flash matching score for objects with different origins is shown in Fig. 12 and does not provide itself an easy discrimination between neutrino and cosmic events.

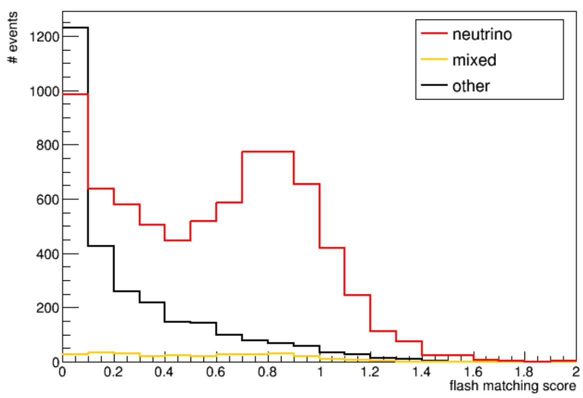
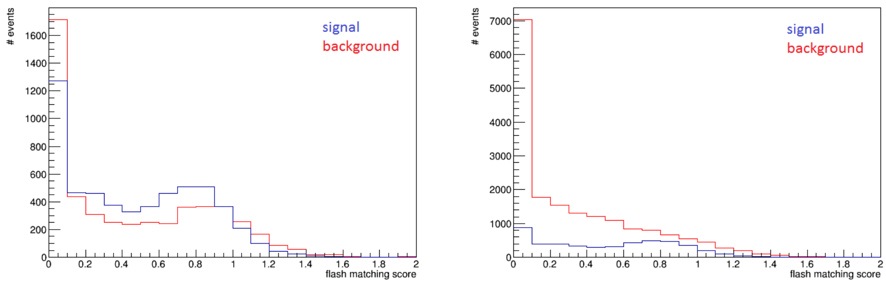


Figure 12: Flash-TPCObject matching score for objects with different origins.

Further analysis focused on only ν_μ CC in FV interactions, called signal events, from objects with either neutrino or mixed origin. The flashmatching score for signal events was compared with score for cosmic objects in Fig. 13a where all the signal events (if the flash matching algorithm worked well) are plotted. This corresponds to 5002 signal events, which gives efficiency of 82%. In the remaining events either no good flashes were reconstructed or the flash-matching algorithm failed. After applying the currently used flash requirement of 50 PE inside the beam spill window, the result changes to Fig. 13b, where the number of events that passed the requirement decreases to 4716 (76% of all signal events from truth information).



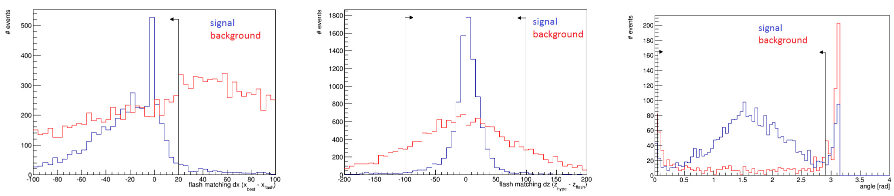
(a) (b)

Figure 13: Flash-TPCObject matching score for ν_μ CC FV interactions (signal) and cosmic background events for all events passing the matching algorithm (a) and for events passing the flash requirement (b).

Other parameters from the flashmatching algorithm:

- minimum track quality
- difference in x position $\delta x = x_{\texttt{best}} - x_{\texttt{hypo}}$
- difference in z position $\delta z = z_{\texttt{flash}} - z_{\texttt{hypo}}$
- angle between two longest tracks (if more than one track was reconstructed)

were studied to look for regions of high signal events purity.



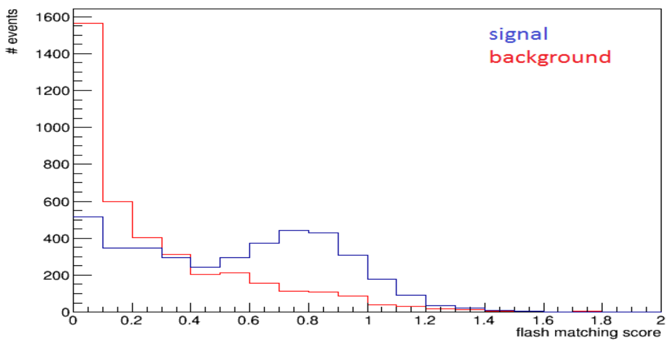
(a) (b) (c)

Figure 14: Cuts on Flash-TPCObject matching variables: δx (a), δz (b), angle (c).

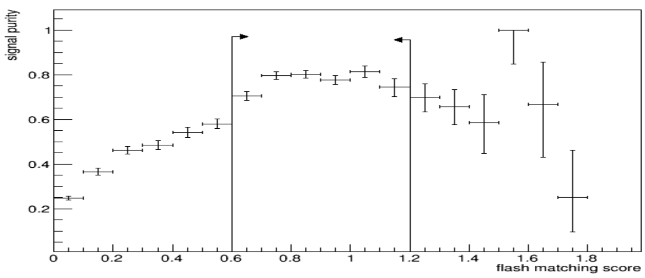
Table 3: Applied cuts on the signal events.

cut	# of events passing	efficiency [%]
no cuts	5002	81
$\geq$ 1 flash with 50 PE	4716	76
min track quality	4644	75
$\lvert\delta z\rvert < 100$cm	4260	69
$\delta x < 20$cm	4205	68
angle $\in (0.05; 2.9)$rad	3953	64

Distributions of those variables (Fig. 14) enable to cut off parts of background events, retaining the regions of enhanced purity in signal events. The performed cuts are shown in Tab. 3. Applying those cuts, the distribution of flashmatching score for signal events shows a range between 0.6 and 1.2, where signal events outnumber the cosmic events, Fig. 15. This region provides relatively high purity of 78% but efficiency of only 23%. Therefore further study of background elimination less harmful to signal events is needed.



(a) Flash-TPCObject matching score for ν_μ CC FV events with applied cuts listed in Tab. 3.



(b) Signal event purity (signal events/all events passing requirements) as function of Flash-TPCObject matching score.

Figure 15

6 Conclusions

Study of the PMT precuts was performed comparing two methods of defining the signal events: currently used OpFlash algorithm with flashes higher than 50 PE inside the beam spill window and the OpHit algorithm including summing PEs from all the PMTs for certain number of time ticks. The study suggested that replacing the currently used flash requirement can lead to increase of signal efficiency by 2.8% causing decrease of background rejection only by 0.2%.

The front porch veto method of eliminating the background events preceding the beam spill window was analyzed. However, introducing the veto, the significant drop in efficiency was observed with no increase in background rejection. Therefore, the veto will not be implemented in further studies.

The matching of flashes and objects detected in the TPC was analyzed and the region of score between 0.6 and 1.2, where the ν_μ CC FV events ave highest purity was determined, based on cuts on multiple flashmatching variables, such as differences in the measured and hypothesis positions, and angle between reconstructed track.

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