Study Towards an Event Selection for Neutral Current Inclusive Single π^0 Production in MicroBooNE

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Abstract

This note describes a Monte Carlo study towards an event selection for the neutrino induced Neutral Current (NC) single π^0 cross section using the MicroBooNE detector. The NC single π^0 channel is especially important in neutrino oscillation experiments as it is one of the main backgrounds in any ν_e or $\overline{\nu_e}$ appearance search. This channel topology has been infrequently measured and the cumulative world data set is limited. The event selection is intended to be entirely based on a fully automated selection process. This note will emphasize the methods used toward selecting the signal topology

Contents

1 Introduction

Neutrino-nucleus cross sections on argon have become an important topic in recent years. Fermilab's neutrino campus provides neutrino beams with energies of the order of a few GeV to many different experiments. The Booster Neutrino Beamline (BNB) provides neutrinos with an average energy of 800 MeV. Positioned along the BNB is the 170t MicroBooNE detector, which is a liquid argon Time Projection Chamber (TPC)[5]. MicroBooNE was commissioned throughout the summer of 2015 and has been taking neutrino data since October of 2015. Over the next few years, the BNB is expected to deliver 6.6×10^{20} Protons on Target (P.O.T) to MicroBooNE allowing for high statistics precision measurements on ν-Ar interactions.

The main purpose of this study is to investigate the selection process needed for measuring a neutral current inclusive cross section on argon. This channel topology has been infrequently measured and the cumulative world data set is limited.[1, 2, 3, 4] Efforts towards mitigating beam related backgrounds, such as other neutrino interaction topologies, will be addressed. The backgrounds coming from cosmic induced π^0s will be discussed.

1.1 MicroBooNE

MicroBooNE's main goals encompass both physics and detector R&D. The first main physics goal is to study the excess of events at low energy previously observed by the MiniBooNE experiment[6]. The second is to measure a large suite of low energy neutrino cross sections on argon. MicroBooNE is the first large scale multi-ton LArTPC that was built, commissioned, and fully operational in the US. The R&D experience gained through this process is invaluable and necessary to demonstrate the scalability of this detector for a future multi-kiloton LArTPC detector.

The core of the MicroBooNE detector is the TPC which forms a rectangular volume of dimensions 2.3 m $\times$ 2.6 m $\times$ 10.4 m and encloses 87t of active LAr. Position and calorimetric reconstruction is done using a wire plane readout. In addition to the wire planes, a light collection system is used to allow for event timing, 3D reconstruction and cosmic-ray rejection.

The TPC readout is comprised of 3 wire planes, one vertical charge collection plane (Y) and two induction planes (U,V) oriented at $\pm 60^\circ$ relative to the Y plane. The 8,256 wires are 150 microns in diameter and are gold coated stainless steel. The three planes are separated by 3mm and have a wire pitch of 3mm which allows for sub-millimeter precision. The wires detect electrons from charged particles that ionize the argon. These electrons are drifted towards the wires through the presence of an electric field in the active region. The complete drift time corresponding to the entire width of the detector is 2.32 ms at an electric field of 273 V/cm.

The MicroBooNE light collection system consists of 32 8-inch Photomultiplier tubes(PMTs) that are located just behind the wire planes. The scintillation light in argon has a wavelength of 128nm and falls in the very ultra-violet(VUV) spectrum[7]. In order to detect this light with conventional PMTs, a tetraphenyl butadiene wavelength-shifting coated plate is placed in front of the PMTs.

Using the known wire positions and arrival time of the drift electron signals in conjunction with the interaction's scintillation light, it is possible to reconstruct the neutrino interaction fully in 3D. Calorimetric information is extracted from the event by converting the collected charge into deposited energy. Candidate neutrino interactions are selected by requiring that the interaction takes place in the detector drift region and is within the 1.6 μs BNB beam spill window.

1.2 Analysis Methodology

A neutrino induced neutral current single π^0 event is defined as a topology that produces one and only one π^0 in the final state with no other charged leptons or mesons originating from the interaction vertex. The reaction is described as $\nu + X \rightarrow \nu + \pi^0 + X$. MicroBooNE, being an LArTPC, has very high quality resolution on vertex activity which will greatly aid in selecting neutral current events.

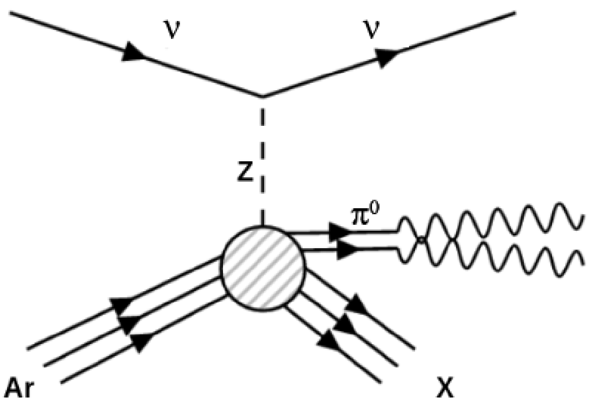

Figure 1: Neutrino induced neutral current single π^0 interaction on argon. In this topology one π^0 is produced and the other particles leaving the interaction (X) but must only consist of nucleons.

MicroBooNE, is located at surface and is therefore subject to cosmic rays that traverse the detector and overall deposit energy throughout the detector. The TPC drift volume will be exposed to a cosmic rate of about 5 kHz of cosmic ray particles. The large flux of cosmic rays make neutrino identification challenging being that each event will have around 10 cosmic particles overlaid in the readout window of 2.3 ms.

This study will focus on understanding each step of a fully automated selection process towards identifying neutral current exclusive single π^0 events. To better understand and isolate the effects of the selection algorithms without any influence from reconstruction inefficiencies, Monte Carlo data objects named Ideal Reconstruction are created. Ideal Reconstruction is a data representation that uses all the MC energy depositions in the detector from a particle and returns the best possible shower or track object as opposed to a Monte Carlo truth study, which has just the true primary particle (neutrino, π^0, photon) information. Ideal reconstruction stores the single objects (tracks or showers) as they would be reconstructed with perfect efficiency. Ideal Reconstruction is therefore a limit of what reconstruction performance can be achieved with actual reconstruction. The track and shower objects are then used to assemble an event interaction [8] [9]. The final cross section analysis on BNB data will run on a full event reconstruction which is currently being developed.

2 Event Selection

The main decay mode of the π^0, with a branching ratio of 98.8%, is $\pi^0 \rightarrow \gamma\gamma$. This allows for a selection topology to reconstruct a π^0 consisting of two shower objects originating from a common vertex. The mean lifetime of the π^0 is very short, $8.4 \times 10^{-17} s$ and can be taken as the neutrino interaction vertex. To identify an event as a NC single π^0 interaction there also must be no muon or charged pion associated with the vertex. Any tracks, such as proton or nuclear recoil, can be associated with the π^0 to form a candidate interaction.

To study each aspect of the selection process a sample of BNB events was generated using GENIE (version 2.8.6)[10]. For the purposes of studying a clean signal sample no cosmic background samples were overlaid. In total, 98,860 neutrino events, using the BNB energy spectrum were generated with a neutrino interaction vertex somewhere inside the cryostat volume. Of this sample, 44,017 events interact inside of the full 87t TPC detector volume. This corresponds to a data sample of 1.19×10^{20} POT delivered from the BNB. Being that MicroBooNE will have some minimum threshold for energy reconstruction, a conservative energy cut is placed on the sample set. Any particle that deposits less that 50 MeV of energy in the detector is considered as invisible with respect to the selection algorithms for this study.

Interaction region	No. Events
All ν interactions	98,860
ν interactions in Cryostat volume	54,843
ν interactions in Border volume	18,821
ν interactions in TPC fiducial volume	25,196

Table 1: Summary of MC neutrino interaction produced from the BNB corresponding to 1.19×10^{20}.

To further define the MC sample, a 27 cm fiducial cut is placed on the true neutrino interaction vertex as shown in Figure 2. The 27 cm length was chosen because it corresponds to 1.5 photon radiation lengths in liquid argon. Neutrino interactions that have a Dalitz decay π^0 are separated from the signal sample and will be accounted for as an inefficiency.

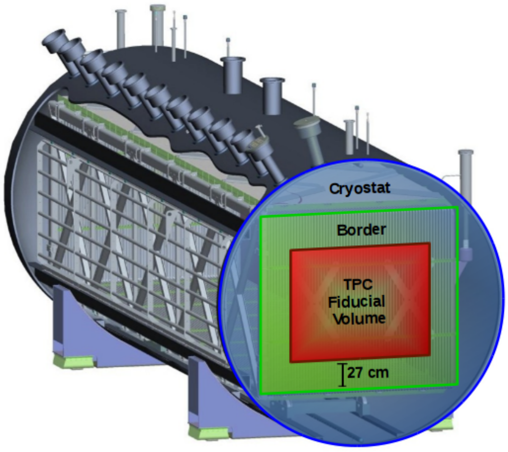

Figure 2: This graphic illustrates the different regions defined inside of the detector which are unique for the NC π^0 analysis. The cryostat volume is shown in blue. The TPC border volume excluded by the fiducial cut defined in the text is shown in green. The TPC fiducial volume is shown in red. Not to scale.

Finally, as shown in Table 2, a total of 1,178 signal events that contain a true NCπ^0 neutrino vertex populate the TPC fiducial volume. This leaves 801 events when applying the energy threshold and Dalitz decay cuts. There are 24,395 background neutrino interactions inside the fiducial volume and 18,821 neutrino events that interact in the region between the TPC edges and fiducial volume (border region) that are considered as backgrounds in this analysis. Finally, outside of the TPC there is an additional 54,843 neutrino events that interact with material inside the cryostat during a beam spill. Once a better understanding of the detector threshold has been achieved the algorithms efficiency will be re-tuned.

Cuts	Signal Events	MC Efficiency
27 cm Fiducial Cuts	1,178	100%
Dalitz Decay	1,164	98.8%
50 MeV Photon Threshold	801	68.0%

Table 2: Summary of BNB MC sample with no cosmic overlaid: First, a fiducial cut of 27 cm is applied to all events in the TPC detector volume leaving 1,178 events that will be considered as signal. The next cut removes events that have a Dalitz decay π^0. The final cut requires that both photons are above 50 MeV in deposited energy.

There are four main stages in the overall selection strategy. In terms of the big picture the steps are as follows:

1. Remove as much cosmic related activity as possible in an event.
2. Search for events that produce one and only one π^0.
3. Decide if the events are neutral current or background.
4. Check to see if timing of the π^0 is consistent with the arrival time of the beam spill.

2.1 Cosmic Removal

Backgrounds coming from cosmic ray particles are removed as follows:

- Tracks that cross at least one TPC wall are tagged as cosmic tracks.
- Any shower that can be tracked back to a cosmic track within 50 cm is then tagged as a cosmic shower.

Tracks or showers that are tagged as cosmic are excluded from being used in further event selection algorithms.

2.2 Single π^0 selection

Showers that were not tagged as being of cosmic origin from section 2.1 are then combined into shower pairs. All possible pair combinations must then pass the following cuts to be considered as a candidate π^0 pair:

- Each shower object must reconstruct to at least 50 MeV in energy to be considered in a shower pair combination.
- Each pair of shower objects must originate from a common vertex. This is done by calculating the 3D distance of closest approach between the two shower axes and requiring that the distance be less than 10 cm as shown in Figure 3.
- The candidate vertex is required to be within 27 cm from all TPC edges.
- The 3D shower opening angle (angle between shower axes) is required to be greater than 17.2° as shown in Figure 4.
- An energy asymmetry cut between the two showers, which is defined in equation 1, is required to be less than 0.8 as shown in Figure 5.

$$E_{\text{asym}} = \frac{|E_1 - E_2|}{E_1 + E_2} \tag{1}$$

Events which have one and only one combination of shower objects that pass all the selection criteria are kept as single π^0 candidates. There are no constraints to reject showers that are not fully contained.

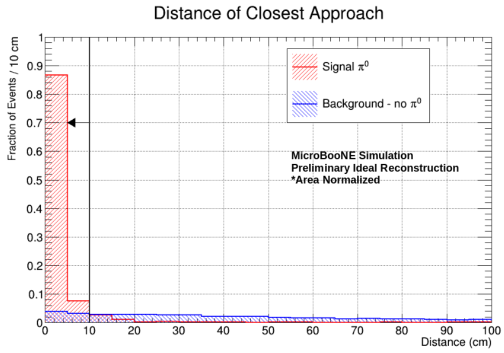

Figure 3: This plots show the distribution of closest approach between shower pairs. The pairs of showers coming from a π^0 have a distance of closest approach that is near 0 cm indicating that they are coming from a common vertex. Events with values in the direct of the arrow are kept.

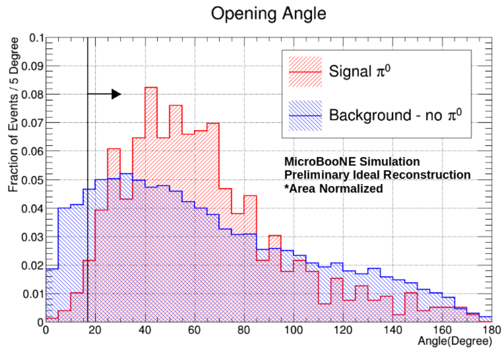

Figure 4: This plots show the distribution of the opening angle between shower pairs. Showers that are nearly collinear are not likely to originate from a π^0. Events with values in the direct of the arrow are kept.

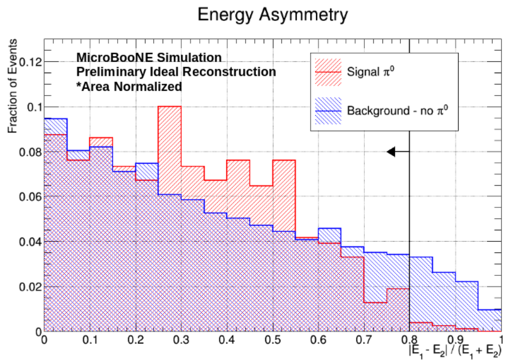

Figure 5: This plots show the distribution of the asymmetry between the energy of the shower pairs. The π^0 will decay isotropically in its rest frame which leads to a nearly flat distribution in shower asymmetry. Events with values in the direct of the arrow are kept.

2.3 NC Selection

Background events from CC interactions are characterized by an accompanying long muon track. Therefore, events that contain only one selected candidate pair are further examined to identify any associated tracks. Tracks with an end point within 10 cm of the vertex between the candidate shower pair are considered to be associated tracks. The following cuts are applied:

- Associated tracks that have an end point within 50 cm of the TPC edges discard the entire event.
- Any event that has an associated track that is longer than 10 cm discard the entire event.

If the event passes the cuts it is labeled as candidate NC single π^0 topology. Events that have no associated tracks also are labeled as candidate neutral current single π^0 topology. No cuts based on track particle identification or vertex track multiplicity are applied.

2.4 Cosmic rejection using Flash Matching

To identify the event as a neutrino interaction the candidate signal interaction topology needs to be in coincidence with the arrival of the neutrino beam spill. This is tested using the prompt light signal produced in the neutrino interaction. The light recorded in several PMTs at the same time is combined into a so-called flash. Flashes are described with a light (P.E.) distribution over time and a weighted physical position in the anode plane. These flashes are then attempted to be matched to a flash hypotheses created based on the showers and tracks involved in the event using ideal reconstruction. If a match is found and the flash is not within the beam gate window of 1.6 μs or an event does not find an associated flash then the event is discarded. For an event in which most of the tracks and showers are properly associated to an interaction the flash matching is very powerful in rejecting cosmic events.

3 Backgrounds

In this section three main backgrounds will be addressed: background neutrino events inside the fiducial volume, neutrino events outside of the fiducial volume, and cosmic background. All of the beam related background are simulated as part of the BNB neutrino sample. The cosmic sample was simulated such that each event is 4.8 ms in duration to correspond to the readout window. The generator used for the cosmic sample was CORSIKA[11] version 7.4003.

The fiducial volume background events consists of actual BNB neutrino interactions that happen inside of the TPC fiducial volume. If the vertex of the π^0 is mis-reconstructed, the algorithm can not properly associate tracks at the vertex. A π^0 event that passes all selection cuts but has no associated tracks is mis-identified as a signal event. This background is dominated by the CC-π^0 interactions which constitute 65.7% of the total topology backgrounds.

The backgrounds from activity in the border and cryostat backgrounds are particularly low and consists of events that interact outside of the fiducial volume but come from a neutrino event in the beam spill window. This volume is categorized into two sections: the border volume which consists of the volume between the edge of the fiducial volume and the TPC, and the cryostat volume which consists of the volume outside of the TPC but within the cryostat. These backgrounds happen from neutrino events in the beam spill window and can not be rejected using out of time flash matching. These backgrounds are driven by the π^0 vertex resolution.

The majority of cosmic rays in the detector will be muons but π^0s can be produced in various secondary interaction modes. In MicroBooNE about half of cosmic π^0s are produced through neutron scattering as shown in Figure 6. Being that neutral particles do not leave a track in the detector, identifying π^0s from a neutron scatter are challenging. A data driven estimate of this background will be taken from beam off cosmic data.

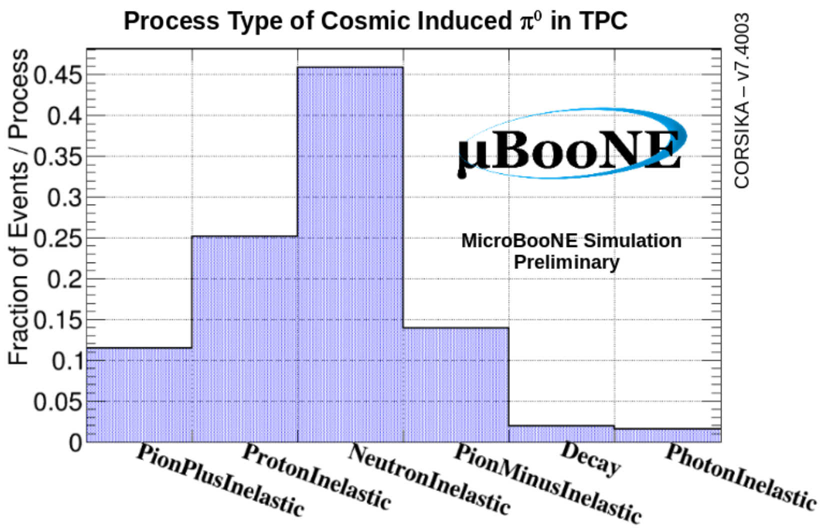

Figure 6: Physical process for cosmic π^0s that decay inside the cryostat. Nearly half of the π^0s enter the TPC through a neutron.

4 Results

BNB simulation produced for MicroBooNE contained a total of 25,196 neutrino events inside the TPC as stated in Table 2. A cut flow is shown in Table 3 to demonstrate the effect of each stage of the selection algorithm. A total of 801 signal events passed the MC cuts. The signal to background ratio for events which have their neutrino vertex inside the fiducial volume is 0.03. This is calculated from 801 total signal events with respect to 24,395 TPC background events. The cut flow for the background samples are shown in Table 4.

Cuts	Signal Events	Efficiency
No. of events	801	100%
Single π^0 Selection	684	85.4%
NC Selection	508	63.4%
Flash Matching	490	61.2%

Table 3: This table shows the signal efficiency as different steps are applied in the selection chain.

Cuts	NC TPC bg	CC TPC bg	Border	Cryostat	Total Rejection Efficiency
No. of events	9,388	15,007	18,821	54,843	0%
Single π^0 Selection	35	67	20	3	99.5%
NC Selection	35	67	11	1	99.88%
Flash Matching	34	64	11	1	99.89%

Table 4: This table shows the total background rejection efficiency as different steps are applied in the selection chain.

To understand the background events containing only cosmic induced events and no neutrino event, we compare to the BNB neutrino event sample in units of beam spill. With a sufficient amount of off beam cosmic data a background for this will be measured. For this study a cosmic scaling is estimated based on equation 2 with the values defined in Table 5.

$$\text{Scale Factor}: \frac{N_{CSel}}{N_{cosmic}} \times \frac{\alpha}{\beta} \times \frac{\omega}{\tau} \tag{2}$$

Variable	Description	Value
N_{CSel}	Number of selected cosmic events that pass cuts	26 events
N_{cosmic}	Total number of cosmic spills	191,800 events
α	Total number of POT corresponding to neutrino sample	1.19×10^{20} POT
β	Average Number of POT per spill	4.6×10^{12} POT/Spill
ω	BNB spill width	1.6 μs
τ	Detector readout window	2.32 ms

Table 5: This is a table of corresponding variables and values for equation 2

After scaling the cosmic sample with equation 2 it is found that 2.4 events would remain as background. This represents the cosmic background that would be coincident with the beam spill window and cannot further be reduced by timing information.

Figure 7 is intended to highlight the ratio of signal and background and does not reflect any momentum measurement. After applying all selection cuts the overall signal efficiency is 61.2%, the overall purity is 81.4%, and the final signal to background ratio 4.4.

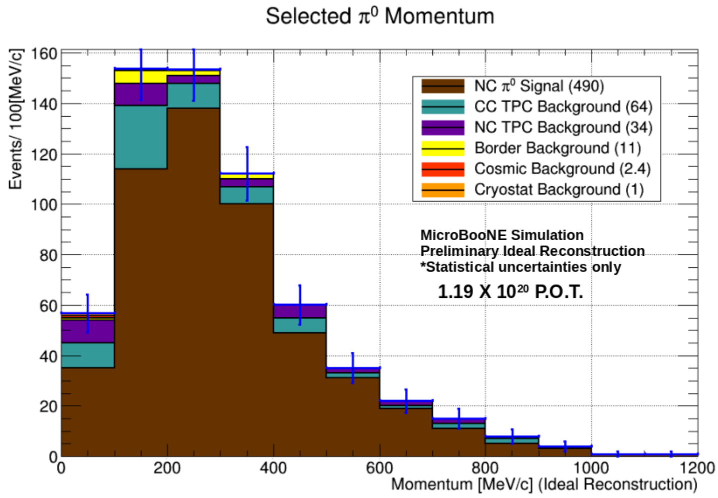

Figure 7: The momentum spectrum plot for selected π^0 BNB events on *Ideal Reconstruction*. It is produced using all shower pairs for BNB events after the cuts described throughout Sec. 2. This plot is intended to show the effect of the signal selection(shown in brown) and background rejection(stacked on top). The signal sample is based on the MC truth definition described in Sec. 2. Since produced with *Ideal Reconstruction*, it doesn't allow any conclusions on the momentum resolution when using actual reconstruction.

5 Conclusions

We have performed a study of the selection efficiency and background rejection for a NC-Single π^0 cross section in MicroBooNE based on *Ideal reconstruction*. The MC-truth based *ideal reconstruction* as a place holder for the actual reconstruction which is actively under development. With the method stated in this note for selecting a neutral current sample seems promising with a purity of 81.4% with minimal expense to signal efficiency(61.2%). We expect that the performance is going to be reduced by the full reconstruction of the events, which is in preparation. This study will require a proper optimization of cuts with full reconstruction and need to include a full treatment of neutrino with overlaid cosmic backgrounds. This channel has been one of the most challenging ones due to statistics, reconstruction limitations and detector effects. In many neutrino experiments this channel is left unmeasured due to the previous mentioned constraints. This study shows that a competitive measurement of this channel from MicroBooNE, even before the full 6.6 $\times 10^{20}$ data set would be available. This cross section on LAr is immediately useful to the neutrino physics community.

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