An Update on MicroBooNE's Inclusive Single Photon Low Energy Excess Search

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Abstract

The MicroBooNE[1] detector is a Liquid Argon Time Project Chamber (LArTPC) detector whose primary design goal is to understand the "low-energy-excess" anomaly seen by MiniBooNE[2]. MicroBooNE's currently published results[3] [4] see no excess consistent with the MiniBooNE observation, emphasizing a need for improved searches in more channels. This note summarizes MicroBooNE's inclusive single photon selection using Wire-Cell reconstruction and pattern recognition, which is used to search for a low-energy-excess (LEE) anomaly in the inclusive single photon channel. The selection is similar to the Wire-Cell inclusive electron neutrino selection[5], but with a different signal definition and some modifications and additions to the pattern recognition tools. A selection with 7.0% efficiency and 40.2% purity is achieved for our targeted single photon signal simulated events.

1 Introduction

This analysis aims to probe the MiniBooNE low energy excess anomaly with an inclusive single photon channel. This note documents the selection for this analysis which uses Boosted Decision Trees (BDTs) trained on Wire-Cell reconstruction and pattern recognition variables. The signal definition for the currently published MicroBooNE single photon analysis[4] is exclusively NC Delta radiative events with either exactly 1 photon and 1 proton or 1 photon and no other particles in the final state. This leaves a large swath of the single photon event phase-space unexplored, particularly for events containing more than one track or containing non-proton-like tracks. Therefore, the goal of this selection is to select a more broad and inclusive set of single-photon-like events. These events can then be further analyzed and fit to evaluate if any significant excess or anomaly is seen. Additionally, this analysis can provide a high-statistics sample of single photon events from Standard Model processes, which are important to further study in order to validate both Standard Model predictions and photon shower reconstruction. Further description of the analysis and selection can be found in prior public notes [6], and in upcoming publications.

2 Signal Definition

The signal for this analysis was chosen to be as inclusive as possible, while also targeting events that could reasonably have contributed to the MiniBooNE low energy excess[2]. Toward this goal, a truth study was performed to determine what currently modeled (i.e. Standard Model-based) processes should be used as signal events for this analysis. The results of this study led to the signal definition and categorization outlined below.

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2.1 Signal Categories

A "single photon signal event" is defined as an event with: (1) exactly one true photon with true kinetic energy above 20 MeV and true shower start (first pair-production) and end (last visible charge) more than 3 cm from the TPC walls, or (2) exactly two true photons, together fitting the previous requirements, from the same source (such as a π^0 decay) that have less than 20° opening angle (a.k.a. are "highly overlapping"), (3) no electrons, and (4) no muons with kinetic energy above 100 MeV.

For analysis purposes the signal events have been placed into five categories:

- ***NC* π^0 *($\rightarrow 1\gamma$)*:** NC events with a π^0 that has decayed into two photons, where one photon does not fit the requirements above, i.e. it does not shower inside the TPC, is below 20 MeV, or has highly overlapping photons. This category makes up 42% of the expected SM signal events before selection.

- ***NC* Δ *1γ*:** An NC $\Delta \rightarrow N\gamma$ decay event where the photon fits the requirements above. This category makes up 2% of the expected SM signal events before selection.

- ***NC Other 1γ*:** Other NC events with a photon fitting the requirements above, but whose true parent is something other than π^0 or Δ, such as ones from higher resonant state particles like η or ρ_0. This category makes up 1% of the expected SM signal events before selection.

- **ν_μ *CC 1γ, $\mu < 100MeV$*:** ν_μCC events with exactly one photon (or two overlapping photons) fitting the requirements above and where the true muon has true kinetic energy less than 100 MeV[1]. This category makes up 9% of the expected SM signal events before selection.

- ***Out of FV 1γ*:** Events with the true neutrino vertex outside the 3 cm fiducial volume (FV) that fits the requirements above. Events in this category can come from any of the above mechanisms, with the distinction that the interaction has occurred outside the FV. Due to the photon conversion distance, the photon can still be contained inside the FV, even when it was originally produced outside. However, any other activity at the vertex, such as any protons, will be outside the FV, and therefore not visible. For this reason, this category is considered separately. This category makes up 46% of the expected SM signal events before selection.

3 Analysis Selection and Efficiencies

In order to reject the extremely large number of backgrounds expected and to select a sufficiently pure sample of single-photons this analysis makes use of two sequential stages, an initial preselection followed by four targeted boosted decision trees (BDTs). The preselection takes place before any training of BDTs and is primarily to reduce any obvious and clear backgrounds, such as cosmic rays, as well as ensuring that the inputs to the BDT are in regions of phase space that are well understood and behave as expected. The preselection consists of three requirements:

- Wire-Cell generic neutrino selection [8], which removes 99.99931% of cosmic ray events
- Reconstructed neutrino vertex in drift direction is > 5 cm from a TPC wall

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[1] 100 MeV was chosen based on MiniBooNE's muon reconstruction threshold. The Cerenkov threshold for a muon in mineral oil is about 40 MeV. However, considering hardware and reconstruction inefficiencies and limitations, it was determined that MiniBooNE was not likely to reliably reconstruct a muon below about 100 MeV in their LEE anomaly result [7].

- At least one reconstructed shower has > 20 MeV energy, to ensure at least one good shower has been found

By far the largest effect comes from the first requirement that the events pass the generic neutrino selection, reducing the event count from over 100,000 cosmic dominated events to a neutrino dominated selection. This selection is shown in Fig. 1 below.

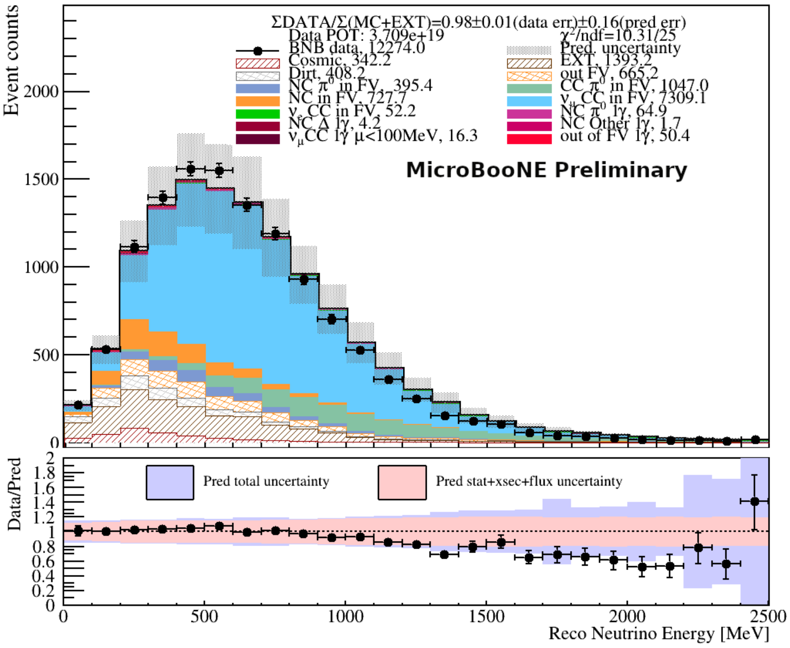
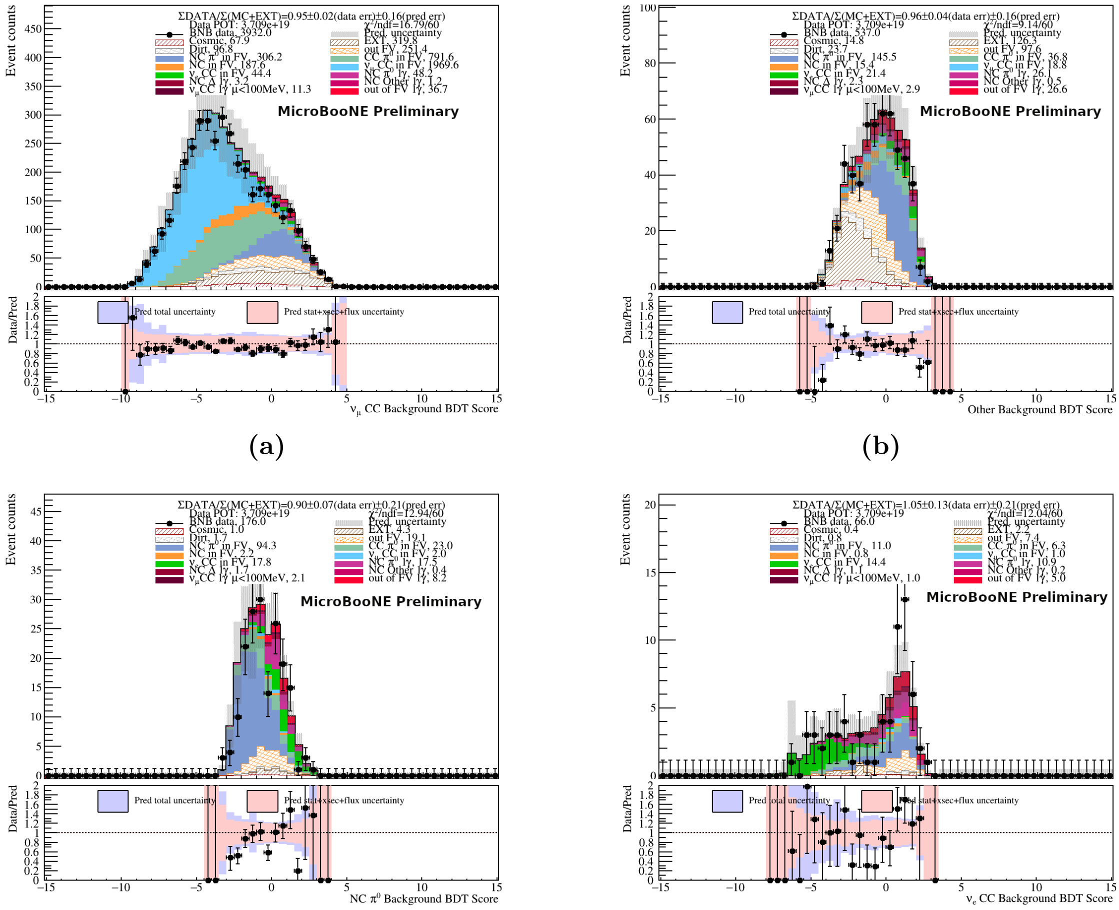


Figure 1: *The reconstructed neutrino energy for all events that pass the generic neutrino selection, the first and primary requirement of the preselection. The data here is a small subset of Run 1 corresponding to* 3.709×10^{19} *POT. The single-photon "signal" events in the shades of pink and red are almost invisible at this stage, swamped by the CC* ν_μ *and cosmic ray events.*

After this preselection, four BDTs are trained to each target one of the remaining major backgrounds. All BDTs use the XGBoost framework[9], and are trained on statistically separate training samples of both signal and specific backgrounds. The four BDTs are as follows

- ν_μ CC background BDT: Targeting all ν_μ CC with and without a π^0 in the final state, with a focus on identifying and rejecting events with long muon-like tracks.
- NC π^0 background BDT: Targeting NC events with a π^0 in the final state. As much of this background is very similar to the single-photon signal events, separation is difficult.
- ν_e CC background BDT: Targeting CC events with a true electron shower, with a focus on calorimetry of the shower start (dE/dx) and shower conversion distances.
- "Other" background BDT: Targeting remaining backgrounds, primarily cosmic induced events and neutrino events in which the true scattering takes place outside of the TPC but charge scatters in and is reconstructed.

The agreement between our simulation and observed data for all input variables, as well as output BDT scores, have been validated against a small sample of open data in Run 1 corresponding to 3.709×10^{19} POT. Figure 2 shows the output BDT scores for each of the four background rejection BDTs. A cut can be placed on these BDT scores, keeping all events above (to the right of the chosen cut). In addition to these cuts, as we are aiming for a true single-photon selection, a requirement to ensure there is exactly 1 reconstructed shower is also implemented after all BDT cuts have been applied. In order to choose the BDT cut positions the values are varied until



(a) **(b)**

(c) **(d)**

Figure 2: *The four output background rejection BDT scores that make up the primary analysis, compared to a small sample of open data in Run 1 corresponding to* 3.709×10^{19} *POT. The analysis proceeds via cuts that are placed on each of these scores to increase the signal purity.*

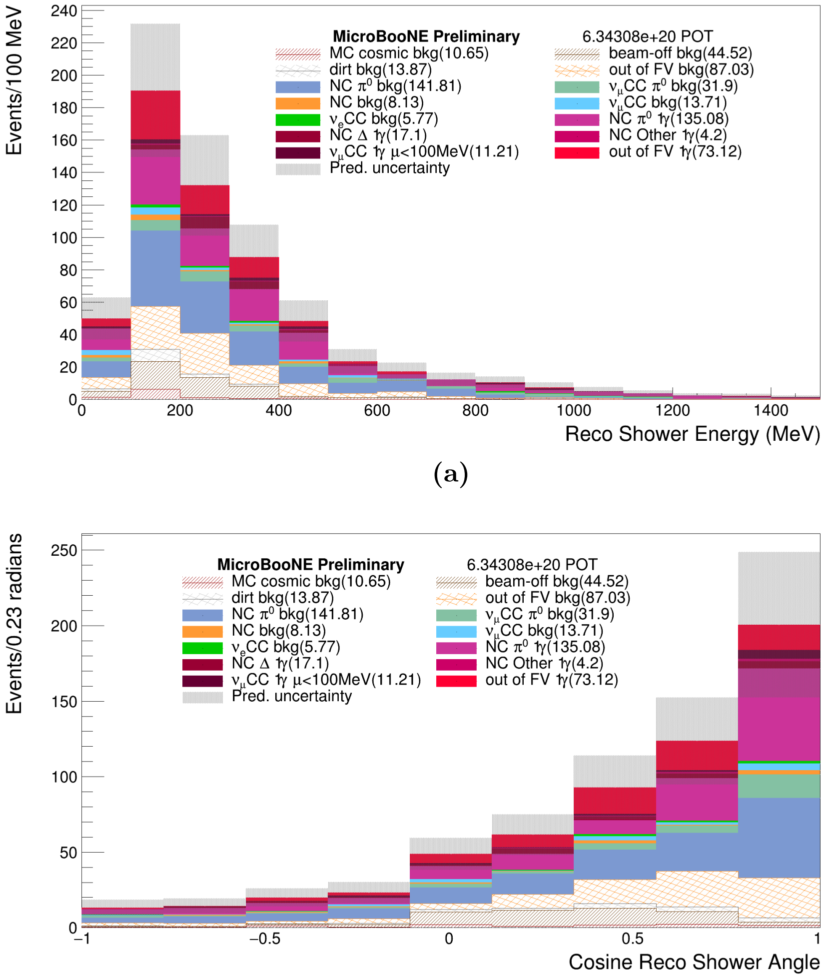
a given metric is maximized. The final selection maximizes the metric efficiency × purity^2 to prioritize achieving a higher purity.

The overall efficiency and purity of the single-photon signal sample after both the preselection, and as we include each background rejection BDT, can be found in Tab. 1.

	Cut Value	Abs. Efficiency	Purity
Generic Neutrino Selection	-	71.7%	1.5%
x vertex position	-	66.2%	1.5%
$\geq$ 1 shower	-	59.9%	2.1%
ν_μ CC BDT	0.4	35.4%	8.0%
Other BDT	0.2	17.9%	14.2%
NC π^0 BDT	-0.05	10.8%	26.7%
ν_e CC BDT	-1.0	8.3%	36.6%
Exactly 1 Shower	-	7.0%	40.2%

Table 1: *Efficiency and purity for the selection, starting from the preselection and highlighting the position of the cut for each of the background rejection BDTs as we sequentially step through them, finally ending with the exactly one reconstructed shower requirement.*

The simulated spectra for all events that pass all BDT requirements, as well as the single-shower condition, is shown in Fig. 3 below. These show the selection covers a very wide range of phase space, crucially including a significant efficiency to lower energy showers ≤ 200 MeV, as well as covering all angles including showers going backwards relative to the beam. This broad phase space ensures that the analysis will be sensitive to a wide range of possible photon-like excesses regardless of the specific kinematics.



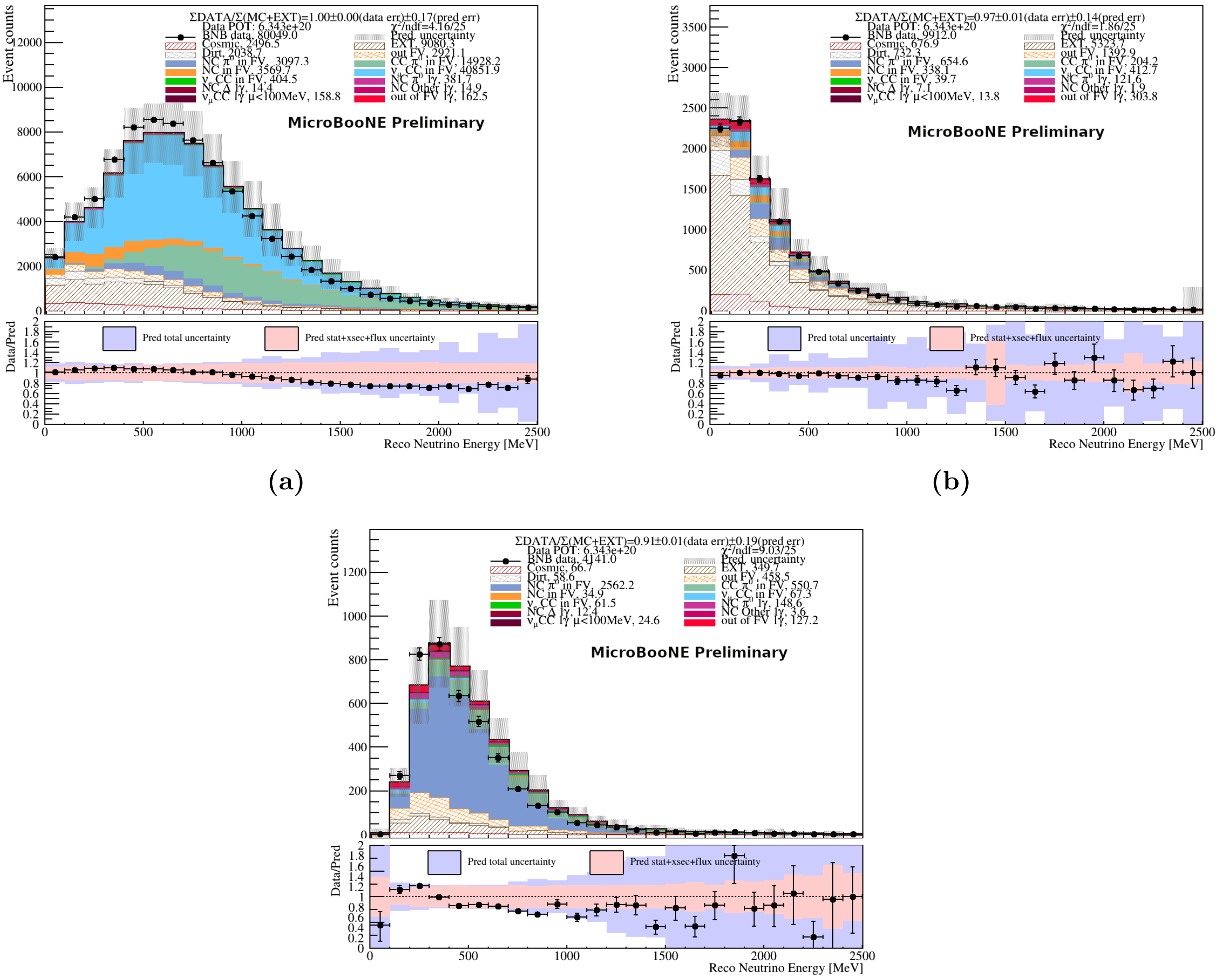
(a)

(b)

Figure 3: *The expected background and single-photon signal distributions, after the selection, in both (a) reconstructed shower energy and (b) angle the shower makes relative to the neutrino beam, scaled to the available Run1-3 data 6.343e20 POT.*

4 Sideband Validation

As this analysis employs a blind analysis strategy to reduce bias, sidebands were used to further validate the agreement between data and Monte Carlo simulations, as well as our background modeling. This analysis utilizes three sideband samples, each approximately corresponding to a primary background that a BDT was specifically trained to remove. Each sideband is defined by reversing the BDT cut to select the background rather than remove it. Figure 4 shows the resulting sideband predictions compared with MicroBooNE Runs 1-3 data for a CC ν_μ, NC π^0, and "Other" background-rich sidebands. In all cases, as well as in many other kinematic variables studied, the data agrees well with the Monte Carlo simulations within our assigned uncertainties. This gives us confidence that our modeling of these backgrounds is sufficient.



(a)

(b)

(c)

Figure 4: *The three high statistics sidebands used to further validate our background simulations.* **a:** *CC ν_μ sideband.* **b:** *"Other" sideband, primarily consisting of non-beam induced events from cosmic rays and beam events that take place outside of the TPC and scatter in.* **c:** *NC π^0 sideband.*

5 Conclusions

This document details updates to MicroBooNE's selection of true single photon events with an inclusive final state topology, defined by one true photon with production and shower start inside the TPC, true energy above 20 MeV, any number of hadrons, and no muons with true energy above 100 MeV. Using Wire-Cell tools from the inclusive electron neutrino LEE analysis, adapted for photons, we developed four BDTs targeting specific backgrounds. The final selection achieves an efficiency of 7.0% and purity of 40.2%. Having validated the background simulation using both a small subset of Run1 open data as well as a suite of high statistics sideband channels, results of this analysis, including detailed goodness-of-fits and comparisons to the observed MiniBooNE excess, are expected soon.

References

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