Final States and Electron-like Background in MicroBooNE

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1 Introduction

Neutrino events in MicroBooNE were simulated using the GENIE neutrino generator. Final state analysis in LArSoft gives the breakdown of event rates for four final state samples: 1) a single μ^+/μ^- in the final state, 2) a single e^+/e^- and no μ^+/μ^- in the final state, 3) a single photon and no μ^+/μ^- or e^+/e^- in the final state, and 4) two photons and no μ^+/μ^- or e^+/e^- in the final state. In addition, the second and third samples are used to make a prediction for the electron-like background in MicroBooNE.

2 Event Rates

Monte Carlo events were generated in LArSoft using the GENIE neutrino generator and the Booster Neutrino Beam flux at 470m (Figure 1). Events were generated in an active volume of 86.7 metric tons for a total POT of 10.3×10^{20}. Final state particles were then propagated through the MicroBooNE LArTPC by LArG4. The total number of Monte Carlo events (scaled to 6.6×10^{20} POT and 60 metric ton fiducial volume) is 181,885.

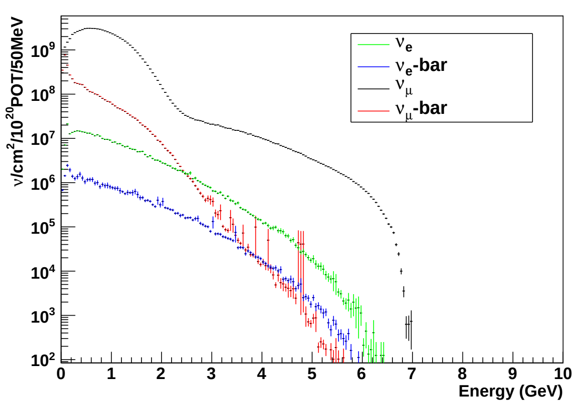

Figure 1: Booster Neutrino Beam Flux at MicroBooNE (470m) for ν_e, $\bar{\nu_e}$, ν_μ, and $\bar{\nu_\mu}$.

Event rates were produced in LArSoft for four different final state samples in MicroBooNE: 1) a single μ^+/μ^- in the final state, 2) a single e^+/e^- and no μ^+/μ^- in the final state, 3) a single photon and no μ^+/μ^- or e^+/e^- in the final state, and 4) two photons and no μ^+/μ^- or e^+/e^- in the final state. Event rates in all of the following tables (excluding the GENIE-NUANCE comparison tables) are scaled to 6.6×10^{20} POT and 60 metric ton fiducial volume.

The rates listed in the column labelled "Primary" in each of the following tables consider final state particles to be only those particles designated as "primary" by GENIE. This includes only the particles that leave the Argon nucleus after a neutrino interaction. However, some events that do not fall into the "Primary" 1 μ, 1 e, 1 γ, or 2 γ final state samples have signatures that *resemble* one of these final states after the primary particles have been propagated through the LArTPC. Because such events could potentially be mis-identified and placed in one of the following samples, the rates for these events ought to be considered as well. The rates for these events are listed in the columns labelled "Additional."

2.1 Single muon sample

Events in the single muon sample include one μ^- or one μ^+ in the final state. The total number of events in this sample (scaled to 6.6×10^{20} POT and 60t fiducial volume) is 131,117. Table 1 shows a further breakdown of this sample by final state. Event rates are shown for all 1 μ final states both with and without a cut on the proton energy. The cut requires protons to have a kinetic energy of at least 50 MeV. Placing this cut greatly reduces the number of events that fall into the $1\mu+ \geq 2p+0\pi$ sample, and greatly increases the number of events that fall into the $1\mu + 0p + 0\pi$ sample.

Figure 2 shows the distribution of muon kinetic energy for all events in the primary 1 muon sample before scaling to the MicroBooNE fiducial volume (blue), after scaling to a 60t fiducial volume (green), and after placing vertex cuts that correspond to a 60t fiducial volume (red). . The vertex cut on the 1 muon sample rejects all events in which the muon's vertex falls outside of the 60t fiducial volume. This vertex cut should reduce the total sample by

$$\frac{Vol_{fiducial}}{Vol_{active}} = \frac{(221 \times 198 \times 1002)\ cm^3}{(256 \times 233 \times 1037)\ cm^3} = 0.71 \tag{1}$$

Scaling the sample to a 60t fiducial volume should reduce the sample by a comparable amount:

$$\frac{Vol_{fiducial}}{Vol_{active}} = \frac{60\ tons}{86.7\ tons} = 0.69 \tag{2}$$

Sure enough, the samples after scaling and after vertex cuts (the green and red histograms in Figure 2) are in good agreement. The locations of muon vertices for events in the primary 1 muon sample, both before and after vertex cuts, are plotted in Figure 3.

Final State	Event Rate (Primary) No Energy Cut	With Energy Cut	Event Rate (Additional) No Energy Cut	With Energy Cut
$1\mu + 0p + 0\pi$	1,809	29,877	0	0
$1\mu + 1p + 0\pi$	51,029	43,483	0	0
$1\mu + \geq 2p + 0\pi$	31,912	11,390	1	1
$1\mu + 0p + 1\pi$	5,922	14,376	591	940
$1\mu + 1p + 1\pi$	19,052	20,771	430	398
$1\mu + \geq 2p + 1\pi$	15,898	5,725	528	211
$1\mu + 0p + \geq 2\pi$	664	1,521	146	387
$1\mu + 1p + \geq 2\pi$	2,180	2,658	194	387
other	2,651	1,316	880	446
total 1 μ events	131,117	131,117	2,770	2,770

Table 1: Rates for 1 muon final states corresponding to 6.6×10^{20} POT and 60 ton fiducial volume. Final states may also include any number of neutrons or de-excitation photons. Rates are shown both with and without a 50 MeV cut on proton kinetic energy.

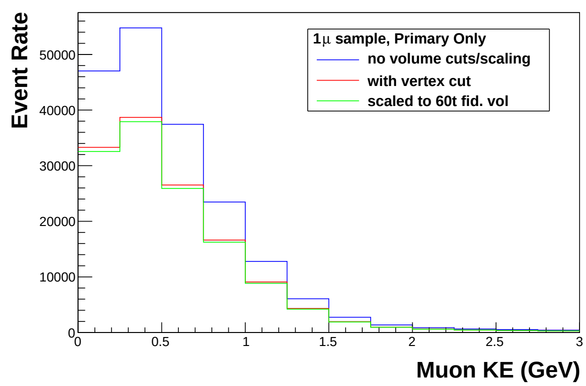

Figure 2: Distribution of muon energy (primary 1 μ events only), scaled to 6.6×10^{29} POT. The blue histogram includes no volume cuts or scaling. The green histogram is scaled to a 60t fiducial volume, and the red histogram includes vertex cuts corresponding to a 60t fiducial volume. Assumes 100% detector efficiency.

Figure 4 shows the distribution of muon kinetic energy for all events in the primary and additional 1 muon samples, after vertex cuts. Most of the muons in the additional 1 muon events sample have energy below 300 MeV.

NUANCE vs. GENIE Event rates for 1 muon final states in GENIE were also compared event rates for 1 muon final states in NUANCE [1]. The GENIE events have been scaled to 6.0×10^{20} POT and 70t fiducial volume in these comparison tables, in order

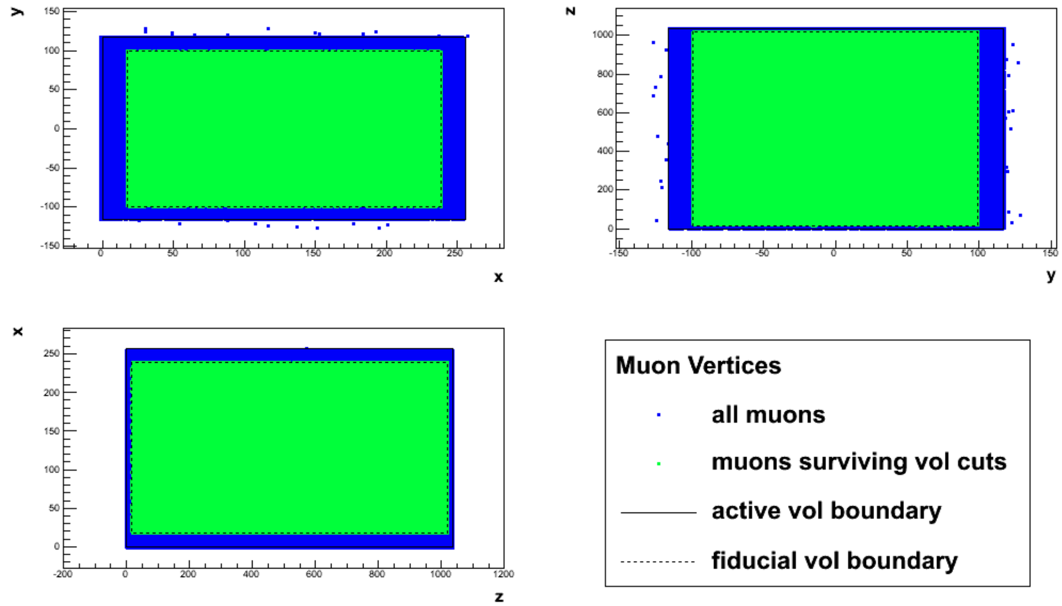

Figure 3: Distribution of muon vertices in the x-y, y-z and z-x planes. A blue dot marks the vertex of any muon in the primary 1 μ sample, and a green dot marks the vertex of a muon that survives the vertex cuts (i.e. lies within the fiducial volume).

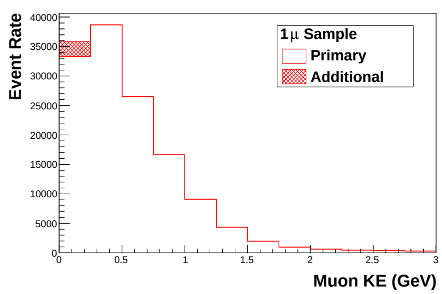

Figure 4: Stacked histogram shows distribution of muon energy for the total 1 muon sample, including both primary 1 μ and additional 1 μ events. Scaled to 6.6×10^{20} POT and include vertex cuts corresponding to a 60t fiducial volume. Assumes 100% detector efficiency.

to match the POT and volume scaling of the NUANCE events. For both NUANCE and GENIE, only primary 1 muon events are considered.

Experimental Signature	Event rate (NUANCE)	Event Rate (GENIE)
$1\mu + 0p + 0\pi$	5	1,918
$1\mu + 1p + 0\pi$	15,158	54,121
$1\mu + \geq 2p + 0\pi$	44,283	33,846
$1\mu + 0p + 1\pi$	915	6,281
$1\mu + 1p + 1\pi$	3,993	20,207
$1\mu + \geq 2p + 1\pi$	14,159	16,862
$1\mu + 0p + \geq 2\pi$	320	704
$1\mu + 1p + \geq 2\pi$	1,556	2,312

Table 2: Rates for 1 muon final states corresponding to 6.0×10^{20} POT and 70 ton fiducial volume. Final states may also include any number of neutrons or de-excitation photons.

Experimental Signature	Event Rate (NUANCE)	Event Rate (GENIE)
$1\mu + 0p + 0\pi$	12,791	31,688
$1\mu + 1p + 0\pi$	21,006	46,118
$1\mu + 2p + 0\pi$	14,680	7,968
$1\mu + 3p + 0\pi$	7,191	2,574
$1\mu + \geq 4p + 0\pi$	3,779	1,537

Table 3: Rates for 1 muon final states corresponding to 6.0×10^{20} POT and 70 ton fiducial volume. Final states may also include any number of neutrons or de-excitation photons.

2.2 Single electron sample

All events with 1 e^+/e^- and 0 μ^+/μ^- in the final state are included in the single electron sample. Table 4 shows a further breakdown of the 1 electron sample by final state.

Figure 6 shows the distribution of electron kinetic energy before scaling to the MicroBooNE fiducial volume (blue), after scaling to a 60t fiducial volume (green), and after placing vertex cuts that correspond to a 60t fiducial volume (red). The vertex cuts on the single electron sample reject all events in which the electron's vertex falls outside the 60t fiducial volume. Again, the 1 e sample after volume scaling and the 1 e sample after vertex cuts are in good agreement. The locations of electron vertices in the primary 1 electron sample, both before and after vertex cuts, are plotted in Figure 5.

Figure 7 shows the distribution of electron kinetic energy for all events in both the primary and additional 1 electron samples, after vertex cuts. The black dashed line represents the sum of the energy distributions for the complete primary 1 electron sample and the additional 1 electron sample after a cut on electron kinetic energy. The cut requires that the electron's kinetic energy be greater than 100 MeV. Few of the additional electron

Final State	Event Rate (Primary) No Energy Cut	With Energy Cut	Event Rate (Additional) No Energy Cut	With Energy Cut
$1e + 0p + 0\pi$	29	189	678	1,492
$1e + 1p + 0\pi$	276	233	1,346	608
$1e + \geq 2p + 0\pi$	198	81	142	66
$1e + 0p + 1\pi$	56	106	1	3
$1e + 1p + 1\pi$	144	156	3	5
$1e + \geq 2p + 1\pi$	110	48	10	6
$1e + 0p + \geq 2\pi$	11	23	1	2
$1e + 1p + \geq 2\pi$	35	42	1	1
other	38	19	4	3
total 1 e events	897	897	2,186	2,186

Table 4: Event rates for Monte Carlo events with 1 electron in final state, corresponding to 6.6×10^{20} POT and 60t fiducial volume. Final states may also include any number of neutrons or de-excitation photons. Rates are shown both with and without a 50MeV cut on proton kinetic energy.

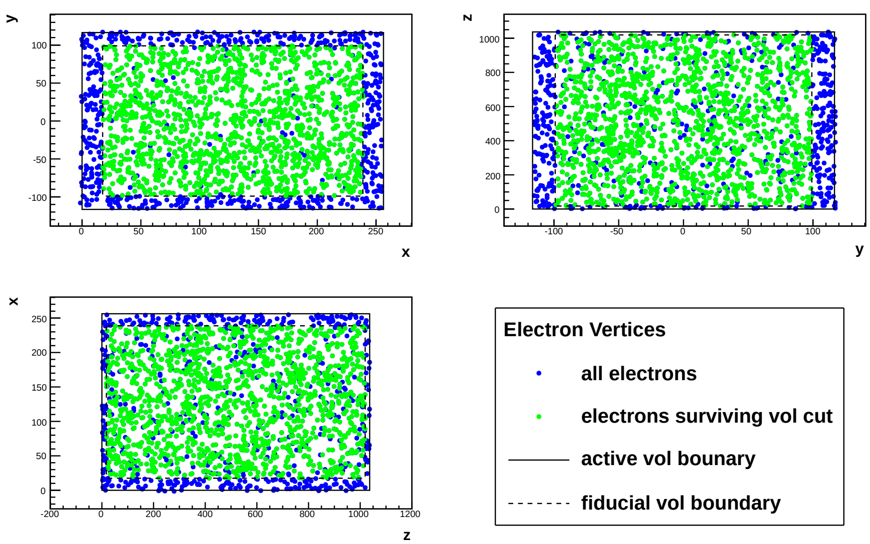

Figure 5: Distribution of electron vertices in the x-y, y-z and z-x planes. A blue dot marks the vertex of any electron in the primary 1 e sample, and a green dot marks the vertex of an electron that survives the vertex cuts (i.e. lies within the fiducial volume).

events do not survive this cut.

Neutrino energy (E_ν^{QE})was reconstructed for 1 electron events using the following for-

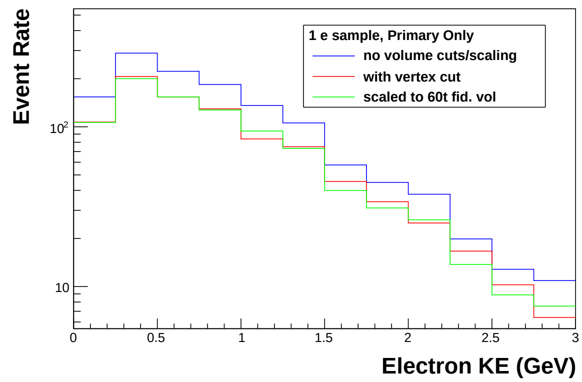

Figure 6: Distribution of electron energy for all events in the primary 1 electron sample, scaled to 6.6×10^{20} POT. The blue histogram includes no volume cuts or scaling. The green histogram is scaled to a 60t fiducial volume, and the red histogram includes vertex cuts corresponding to a 60t fiducial volume. Assumes 100% detector efficiency.

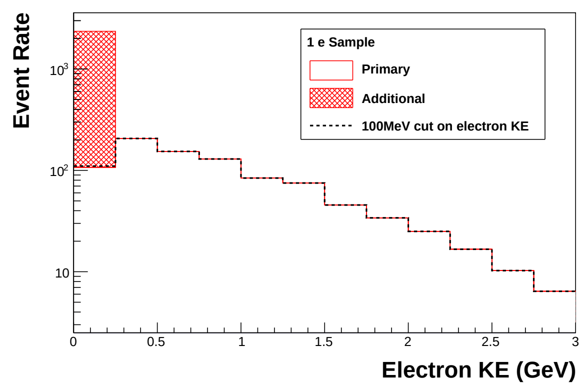

Figure 7: Stacked histogram (red) shows distribution of electron energy for the total 1 electron sample, including both primary 1 e and additional 1 e events. The overlaid dashed line (black) marks the distribution of electron kinetic energy after placing a 100 MeV cut on the KE of electrons in the additional 1 e sample. Most of the additional events are eliminated by this cut. Scaled to 6.6×10^{20} POT and includes vertex cuts corresponding to a 60t fiducial volume. Assumes 100% detector efficiency.

mula:

$$E_\nu^{QE} = \frac{2M_n E_e + M_p^2 - M_n^2 - M_e^2}{2(M_n - E_e + \mathbf{p}_e \cdot \mathbf{u}_\nu)} \tag{3}$$

Figure 8 shows the distribution of E_ν^{QE} (calculated for all primary 1 e events) before scaling to the MicroBooNE fiducial volume (blue), after scaling to a 60t fiducial volume (green), and after placing vertex cuts that correspond to a 60t fiducial volume (red).

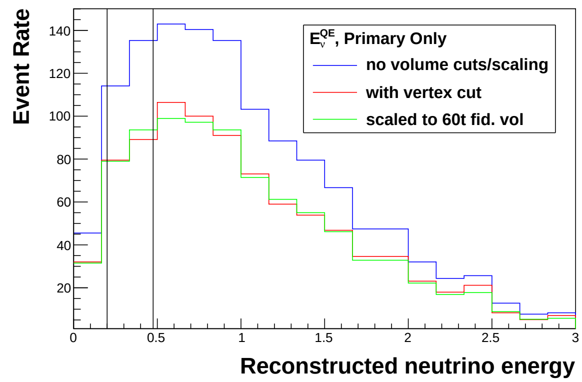

Figure 8: E_ν^{QE} for all events in the primary 1 electron sample, scaled to 6.6×10^{20} POT. E_ν^{QE} is calculated using the electron energy and Equation 3. The blue histogram includes no volume cuts or scaling. The green histogram is scaled to a 60t fiducial volume, and the red histogram includes vertex cuts corresponding to a 60t fiducial volume. Assumes 100% detector efficiency.

For CCQE events, the Equation 3 should give an accurate energy for the neutrino. E_ν^{QE} should be approximately equal to true neutrino energy for CCQE events with $1e + 0p + 0\pi$ or $1e + 1p + 0\pi$ final states. Figure 9 plots E_ν^{QE} vs. true neutrino energy for these final states and shows that this is indeed the case.

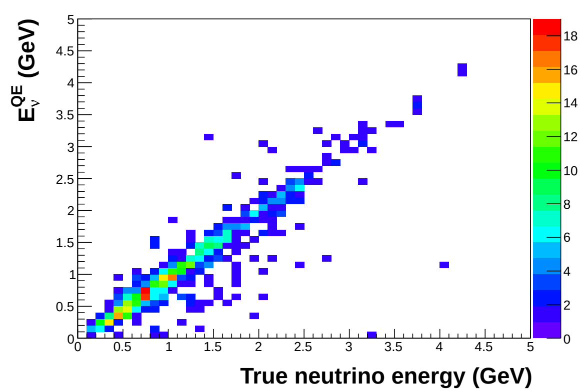

Figure 9: Cross check of E_ν^{QE} vs. true neutrino energy for events in the primary 1 electron sample with either $1e + 0p + 0\pi$ or $1e + 1p + 0\pi$ in the final state.

2.3 Photon samples

Events with 0 μ^+/μ^-, 0 e^+/e^-, and at least one π^0 or photon in the primary final state are placed into the sample of primary photon events. All primary photons and daughters of primary π^0 are considered in these primary photon events. Events with 0 μ^+/μ^-, 0 e^+/e^-, and at least one photon in the event are placed into the sample of additional photon events. In these additional events, all photons are considered. Before vertex cuts, events with one photon are placed into the 1 photon sample, and events with 2 photons are placed into the 2 photon sample. Because most of the events in the photon sample are NC π^0 events, which produce two photons ($\pi^0 \to \gamma + \gamma$), the 1 photon sample before vertex cuts is very small.

The vertex cuts for the photon samples are as follows. Events are placed in the 1 photon sample if one photon converts to e^+e^- inside the fiducial volume, and no other photon converts inside the active volume. This vertex cut is expected to increase the 1 photon sample: in some NC π^0 events, one photon converts to e^+e^- inside the fiducial volume, while the other photon converts outside of the active volume. Because the second photon escapes detection, such events appear in the detector as single photon events. This happens frequently for events in which the initial neutrino interaction occurs near the edge of the fiducial volume. The photon conversion points and neutrino vertices for events in the primary 1 photon sample (after vertex cuts) are shown in Figure 10. As expected, the neutrino vertices for these events (red) and the photon conversion points (green) lie mostly near the edges of the fiducial volume. Events are placed in the 2 photon sample if two photons convert to e^+e^- inside the fiducial volume, and no other photons convert inside the active volume. All other photon events are disregarded. Table 5 shows the event rates for the 1 photon and 2 photon samples before and after vertex cuts. Figure 11 shows the distribution of photon energy for the 1 photon and 2 photon samples before and after vertex cuts.

Experimental Signature	Event Rate (Primary)	Event Rate (Additional)
Total Number of γ events	$14,501$	$10,305$
1 γ sample before vertex cuts	152	$1,237$
1 γ sample after vertex cuts	954	$1,134$
2 γ sample before vertex cuts	$13,677$	$2,886$
2 γ sample after vertex cuts	$7,867$	$1,780$

Table 5: Event rates for 1 photon and 2 photon samples, before and after vertex cuts corresponding to a 60t fiducial volume. Scaled to 6.6×10^{20} POT.

Figure 12 shows the distribution of all 1 photon and 2 photon events, including both

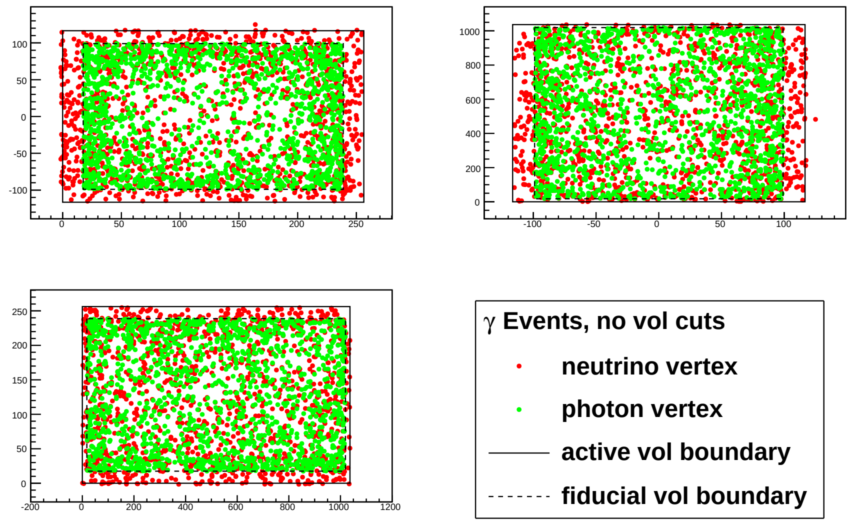

Figure 10: Distribution of neutrino vertices and photon conversion points in the x-y, y-z and z-x planes for events that fall into the primary 1 photon sample (after vertex cuts). A red dot marks the vertex of a neutrino, and a green dot marks the point where a photon converts to e^+e^-.

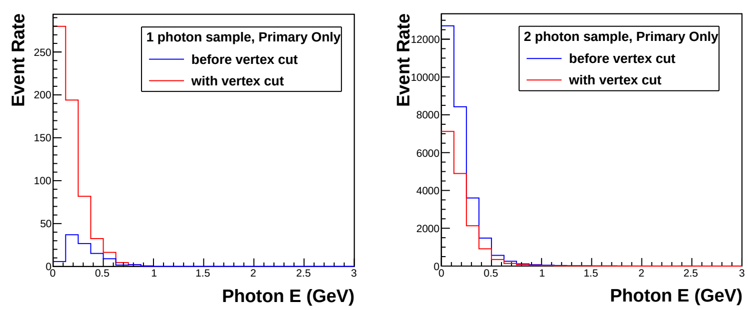

Figure 11: Distribution of photon energy for all events in the primary 1 photon sample (left) and primary 2 photon sample (right). Each photon in the 2 photon sample is counted separately. Both are scaled to 6.6×10^{20} POT. Blue marks the distribution before vertex cuts are applied, and red marks the distribution after applying vertex cuts which correspond to a 60t fiducial volume. Assumes 100% detector efficiency.

primary and additional photon samples. The photons in all additional 1 photon and 2 photon events have energy less than 200 MeV.

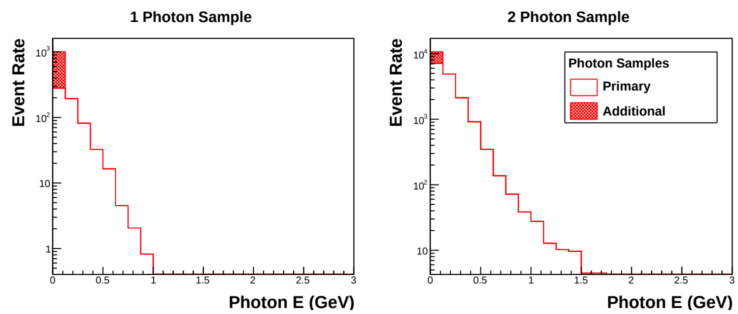

Figure 12: Stacked histogram shows the energy distribution for all events in both the primary and additional 1 photon samples (left) and primary 2 photon samples (right), after vertex cuts. Each photon in the 2 photon sample is counted separately. All photons in the additional 1 photon and 2 photon samples have energies below 200 MeV. Both histograms are scaled to 6.6×10^{20} POT. Assumes 100% detector efficiency.

3 Estimates for Background in MicroBooNE

An estimate for the electron-like background in MicroBooNE was made by considering the events in the 1 electron sample with CCQE-like final states ($1e + 0\pi$). The distribution of E_ν^{QE} for all events in the 1 electron sample, broken down by final state, is shown in figure 13. Only the final states $1e + 0p + 0\pi$, $1e + 1p + 0\pi$, and $1e+ \geq 2p + 0\pi$ are considered in the prediction for electron-like background. Because there are hardly any "additional" 1 electron events or 1 photon events that contribute to the background prediction for energies greater than 100MeV, only primary 1 electron events and primary 1 photon events are considered in the background predictions.

The prediction for electron-like background in MicroBooNE (Figure **??**) is scaled to 6.6×10^{20} POT and includes vertex cuts corresponding to a 60t fiducial volume. The prediction is also scaled to the efficiency for MicroBooNE, which is 80%. In addition to the CCQE-like 1 electron events, the background prediction includes 6% of the single photon events (after vertex cuts). This represents the number of single photon events that will be misidentified as single electron events. E_ν^{QE} for the single photon events was calculated using Equation 3, with the photon energy substituted for the electron energy.

3.1 Comparisons

Figure 15 compares the new prediction made above to a prediction calculated from MiniBooNE data [3]. The MiniBooNE prediction is scaled to 6.6×10^{20} POT, 70t fiducial volume, and 80% efficiency. For the sake of comparison, the new prediction in Figure 15 is also scaled to 6.6×10^{20} POT, 70t fiducial volume, and 80% efficiency. In addition, the

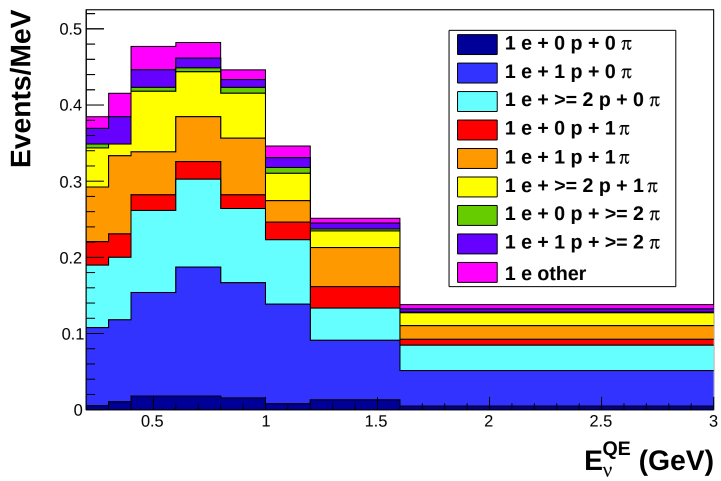

Figure 13: E_ν^{QE} for all primary single electron events, broken down by final state. Scaled to 6.6×10^{20} POT and 80% detector efficiency, and including vertex cuts corresponding to a 60t fiducial volume.

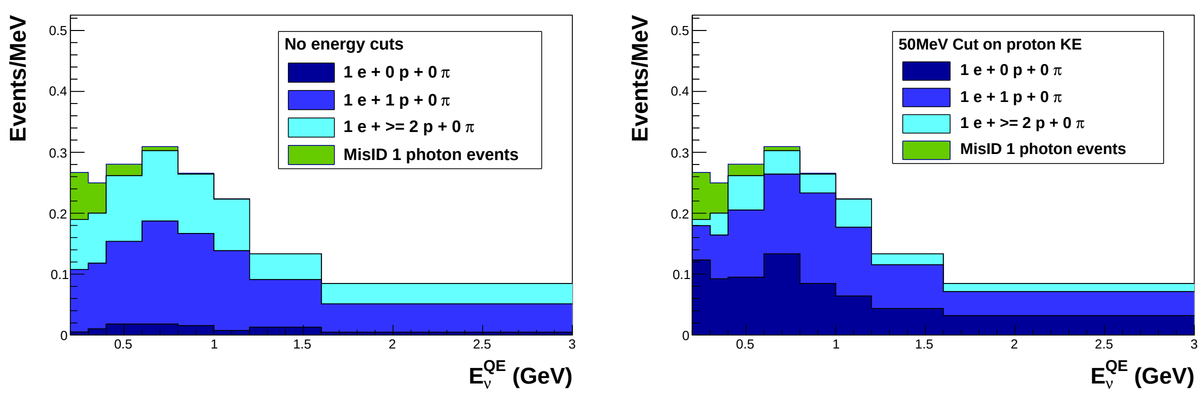

Figure 14: Prediction for electron-like background in MicroBooNE. E_ν^{QE} for all CCQE-like single electron events ($1e + 0\pi$ in the final state). Also includes 6% of 1 photon events (after vertex cuts) as mis-ID 1 photon events. The left plot shows the composition of the background before making any cuts on proton energy, and the right plot shows the composition of the background after making a 50 MeV cut on the proton kinetic energy. Both are scaled to 6.6×10^{20} POT and 80% detector efficiency, and include vertex cuts corresponding to a 60t fiducial volume.

new prediction has been scaled by a factor of

$$\frac{(r_{\mu BooNE})^2}{(r_{MiniBooNE})^2} = \frac{(470m)^2}{(540m)^2} = 0.76 \quad (4)$$

in order to account for the difference in flux at MiniBooNE (540m) and MicroBooNE (470m). Additional differences in the prediction are to be expected, due to differences in neutrino cross sections on Carbon and on Argon.

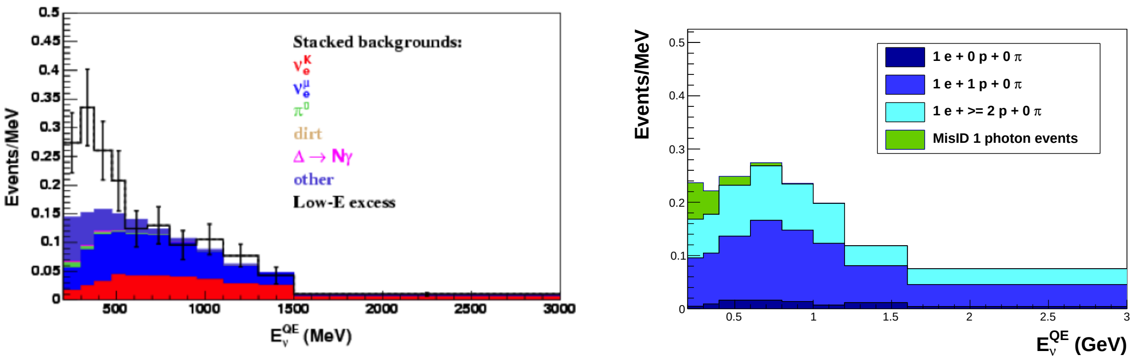

Figure 15: (Left) Background predictions for MicroBooNE calculated using MiniBooNE event rates. Scaled 6.6×10^{20} POT, 70t fiducial volume, and 80% efficiency. (Left) E_ν^{QE} for CCQE-like 1 electron events only (final states including 1 e and 0 π). Mis-ID photon events are shown in green. Scaled to 6.6×10^{20} POT, 70t fiducial volume, and 80% efficiency, for the sake of comparison. In addition, this prediction is scaled to account for differences in flux (See Equation 4).

Figure 16 compares the new prediction to a prediction calculated in LArSoft using an older generation of GENIE events. These older events were generated for a total POT of 6.0×10^{20}. Both the new prediction and the older LArSoft prediction are scaled to 6.6×10^{20} POT, 60t fiducial volume, and 80% efficiency.

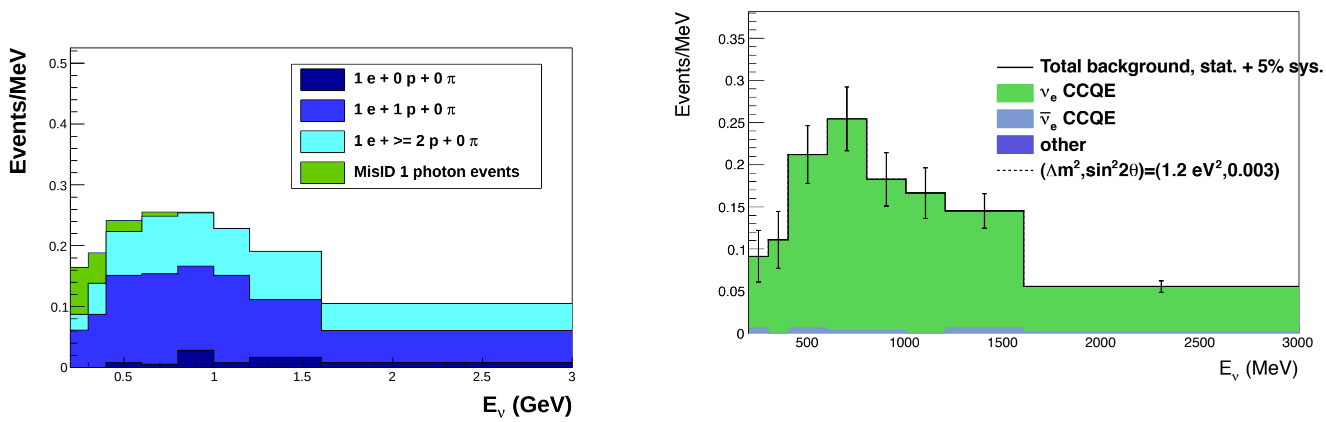

Figure 16: (Left) True E_ν for CCQE-like 1 electron events only (final states including 1 e and 0 π). Mis-ID single photon events are shown in green. Scaled to 6.6×10^{20} POT, 60t fiducial volume, and 80% efficiency. (Right) Background predictions for MicroBooNE calculated in LArSoft using a older generation of GENIE events. Also scaled to 6.6×10^{20} POT, 60t fiducial volume, and 80% efficiency.

References

[1] MicroBooNE docdb #2055

[2] MicroBooNE docdb #1765

[3] MicroBooNE docdv #366

A Final State Analysis in LArSoft

- GENIE events were generated using the flux found in /uboone/data/flux_normalized/mc_nu_mb470_r200_GENIE.root.
- Events (before LArG4 and DAQ) can be found in /uboone/data/SBL_focus_studies/ub470/outputs.
  After LArG and DAQ:
  /uboone/data/users/jennetd/ub_larganddaq_noEMDaughters/outputs.
- LArSoft analysis package can be found in /uboone/app/users/jennetd/myart_S2012.05.09/BackgroundAnalysis.
  Note: There are separate versions of BackgroundAnalysis.cxx for the primary final states analysis (stored in BackgroundAnalysis_Primary.txt) and the additional events analysis (stored in BackgroundAnalysis_AllFSI.txt).
- Root macro used to make all plots and tables found in this note: /uboone/app/users/jennetd/myart_S2012.05.09/NewSampleMacro.c