MC performance study for an early ν_μ charged-current inclusive analysis with MicroBooNE

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Abstract

This note describes an analysis performed on Monte Carlo data to evaluate the sensitivity of MicroBooNE for an early ν_μ charged-current inclusive cross section measurement. Such an analysis is intended to be done using the first three months of Booster Neutrino Beam data. The event selection is entirely based on an automated event reconstruction. The Monte Carlo prediction for a flux-integrated and single differential cross section measurement with an approximate estimation of statistical and systematic uncertainties for the MicroBooNE detector as designed is presented. This allows the comparison of the sensitivity of MicroBooNE to theory and other experiments.

1 Motivation

The primary purpose of this study is to demonstrate the performance of MicroBooNE [1] for a first charged-current (CC) ν_μ inclusive cross section measurement using a small set of collected data and a basic set of reconstruction tools. The analysis is based on Monte Carlo (MC) simulation for the MicroBooNE detector as designed and uses full event reconstruction. This study also demonstrates the current performance of a fully automated reconstruction chain and cosmic removal techniques, both of which are critical for surface liquid-argon time projection chamber (LArTPC) detectors.

Note that the analysis method, event selection, and estimates of systematic uncertainties presented in this note are not final and are expected to change after first experimental data has been evaluated and the simulation has been adjusted to current running conditions.

2 The MicroBooNE LArTPC

A LArTPC consists of a cathode and anode planes enclosed in a volume of highly purified liquid argon (LAr). Charged particles produced, in e.g. neutrino interactions, within the liquid argon cause ionization and excitation of the argon. A large electric field drifts these ionization electrons towards finely segmented anode wire planes oriented at different angles to provide stereoscopic views of the same interaction. The excitation of argon produces prompt scintillation light giving important timing information about the neutrino interaction.

MicroBooNE is an 89-ton active volume LArTPC neutrino experiment built on the Fermilab Booster Neutrino Beamline (BNB). MicroBooNE finished commissioning in summer 2015 and has been taking data with the BNB since October 2015. Its main physics goals are the investigation of the low-energy excess of electron neutrino-like events seen previously by MiniBooNE [2], and high-statistics precision measurements of ν-Ar interactions in the 1 GeV range.

The volume of liquid argon in the MicroBooNE LArTPC drift region is about 89 t. The distance between cathode and anode is 2.56 m and an ionization electron takes about 2.3 ms to travel the full drift distance at an electric field of 273 V/cm. The anode region consists of three wire planes oriented at an angle of 60° with a total of about 8000 wires. The spacing between consecutive wires and wire planes is 3 mm. The MicroBooNE light collection system consists of 32 8-inch PMTs that are located just behind the wire planes and detect VUV scintillation light using a TPB-based wavelength-shifting coating.

2.1 Event reconstruction

Event reconstruction is done automatically using the LArSoft [6] software package. This study uses simulated data reconstructed with the information from the TPC and light system. The first step of reconstruction searches for ionization signals on each wire and finds *hits* that indicate localized energy depositions above a certain threshold. Reconstructed hits in each wire plane are then grouped into *clusters* based on their proximity to one another. The second step of reconstruction matches groups of 2-D hits or clusters from three readout planes to obtain 3-D *tracks* and *showers*. A vertex finding algorithm then examines the end points of tracks and showers to determine which come from a common origin and finds vertices.

3 Expected signal and background rates

The neutrino signal expectation is taken from BNB events generated using GENIE (version 2.8.6) [3], and propagated through the detector simulation and full reconstruction as described in the previous section. For this study, a total of 5.3×10^{19} protons on target (POT) is used, which is expected to be accumulated in about three months assuming the BNB is running at 1 Hz at an intensity of 5×10^{12} POT per beam spill. Every beam spill triggers the data taking in MicroBooNE. However, only 1 in about 660 recorded events will contain a neutrino interaction [4]. A recorded event in MicroBooNE has a duration of 4.8 ms. This is extends to both sides beyond the time that it takes for ionization electrons to drift the entire distance from the cathode to the anode (drift time), which is approximately 2.3 ms at initial running conditions.

Since MicroBooNE is located only a few meters below the surface, a large flux of cosmic-ray induced particles, in particular muons, enter the detector volume. On average, 24 to 36 muons are expected in the TPC active volume per recorded event. The cosmic-ray background forms the dominant background for any beam-related analysis in MicroBooNE. For the signature of a CC neutrino interaction, cosmic muons are the most problematic background. Cosmic muon background rates for this study are estimated using the CRY [5] simulation. For the final analysis on experimental data, this background will be derived from the off-beam (cosmic) data.

Additional background is arising from beam-related or cosmic interactions taking part outside of the TPC active volume. Such interactions can cause tracks that enter the TPC active volume, or cause optical activity that is recorded by the light system without corresponding TPC activity. Such background is not included in this study, but is currently being studied.

4 Event selection

4.1 Cosmic removal

The overwhelming background of recorded events containing only cosmic-ray particles are removed using the following strategies:

- As explained above, a recorded event has a duration of 4.8 ms, while the beam spill window that contains BNB neutrinos is only 1.6 μs long. Events with no optical signal (above a threshold of 50 photoelectrons) in coincidence with the beam spill window are rejected.
- Optical signals are matched with 3-D tracks and showers based on the 2-D position of the PMT and the 3-D object. Objects with an optical signal not in coincidence with the beam spill window cannot originate from a neutrino interaction and are removed.
- Tracks that cross the entire TPC volume, or tracks which are entering or exiting are tagged as cosmic tracks and are excluded from further analysis[1].

Using the above strategies, the efficiency of rejecting events that do not contain a neutrino interaction is 99.87%, based on an as-designed detector MC.

4.2 Signal selection

Events passing all the cosmic removal cuts described in the previous section represent candidate neutrino events and are further considered for analysis. The following cuts are applied:

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[1] This restricts this initial study to only contained events. The inclusion of exiting tracks in the analysis is currently being explored.

- For each remaining candidate neutrino-induced track the closest reconstructed vertex is found. This vertex must be inside the detector fiducial volume defined as 5 cm from all sides of the TPC. If the distance between the vertex and track in this vertex-track pair is smaller than 5 cm, the pair further qualifies as a charged-current neutrino interaction.
- Out of all vertex-track pairs in an event fulfilling the above requirement, the pair containing the longest track is selected. If this track is longer than 0.75 m, it is considered a muon candidate and the corresponding vertex represents the neutrino interaction vertex.

Table 1 shows the final signal and background event rates after the event selection. The overall efficiency – which includes acceptance effects – of this selection is about 30%. The low efficiency is mainly due to the current requirement of a contained muon track.

5 Cross section calculation

The total flux-integrated cross section is calculated using the equation,

$$\sigma = \frac{N_{\text{measured}} - N_{\text{BG}}}{\epsilon \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu}}, \tag{1}$$

where ϵ is the efficiency of the event selection based on MC, N_{target} is the number of target nucleons, and Φ_{ν_μ} is the BNB muon neutrino flux integrated over energy and scaled to the corresponding POT used in the analysis (see Figure 1). All the parameters used for the calculation with their statistical and systematic uncertainties are given in Table 1.

Systematic uncertainties on background numbers derived from Monte Carlo are estimated conservatively. The flux uncertainty is also estimated conservatively based on Ref. [7]. The uncertainty on the number of target nucleons is taken from Ref. [8].

In addition to a flux-integrated cross section, the predicted result is also reported as a differential cross section as a function of muon kinematics, such as the muon momentum p_μ, which is calculated from the muon range. In this case, signal and background event rates as well as efficiencies are binned as a function of muon momentum. The differential cross section calculation is done using the following equation,

$$\frac{d\sigma}{dp_{\mu,i}} = \frac{\sum_j U_{ij} \cdot (N_{\text{measured},j} - N_{\text{BG},j})}{\epsilon_i \cdot \Delta p_{\mu,i} \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu}} \tag{2}$$

where i is the corresponding bin in true p_μ and j is the corresponding bin in reconstructed p_μ. The matrix U_{ij} is the unsmearing matrix that is derived from simulation. After the background subtraction, the simulated data is unsmeared, before it is corrected for efficiency. Both, the unsmearing matrix and the efficiency correction, are steps that depend on the cross section modeling. This model dependence is not further taken into account in this study, but is currently under investigation.

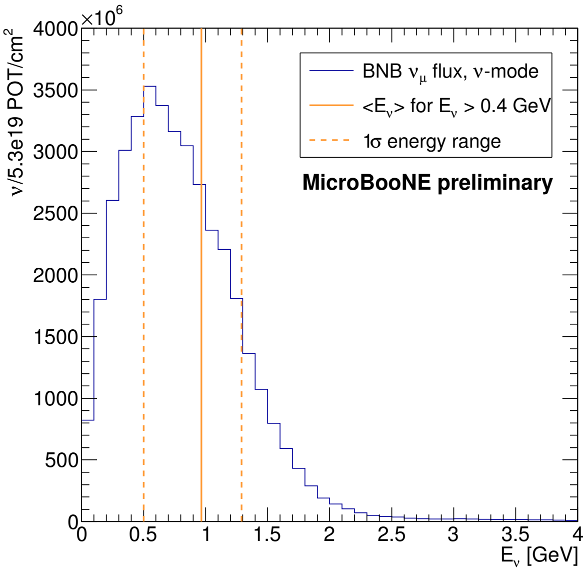

Figure 1: BNB ν_μ flux for neutrino mode running shown on a linear scale. The lines mark the mean neutrino energy and the 1σ range taking into account only energies $E_\nu > 0.4$ GeV, which results in a mean neutrino energy of 967^{+323}_{-467} MeV.

Simulation for MicroBooNE as designed	MC events/ variable	Stat. unc.	Rel. stat. unc.	Sys. unc.	Rel. sys. unc.
Predicted no. of events	7968	89.3	1.1%	-	-
Cosmic only events	3401	-	-	58.3	1.7%
Cosmics in BNB events	261	-	-	130.5	50%
NC events	156	-	-	78	50%
ν_e and $\bar{\nu}_e$ events	22	-	-	22	100%
$\bar{\nu}_\mu$ events	12	-	-	2.4	20%
Total background	3852	-	-	164.3	4.3%
ν_μ CC events	4116	89.3	2.3%	164.3	4.0%
Φ_{ν_μ}	3.10×10^{10} cm^{-2}	-	-		12%
N_{target}	4.76×10^{31}	-	-		2%
ϵ	0.326	-	-		5%

Table 1: Number of MC events for the CC inclusive selection using 5.3×10^{19} POT of BNB simulated data for a detector as designed. Rates are further divided into expected signal and background rates based on MC information. Backgrounds estimated from MC will be derived from a sufficient sample of generated events such that their statistical error can be neglected. The estimation of cosmic only background in the experiment is going to be be data-driven. Therefore, assuming that the same amount of off-beam as on-beam data will be used for background estimation, the statistical uncertainty is just given by $\sqrt{3401} = 58.3$, and will enter the overall uncertainty as a systematic uncertainty. Efficiency, flux and number of target nucleons with assumptions for systematic uncertainties are also listed.

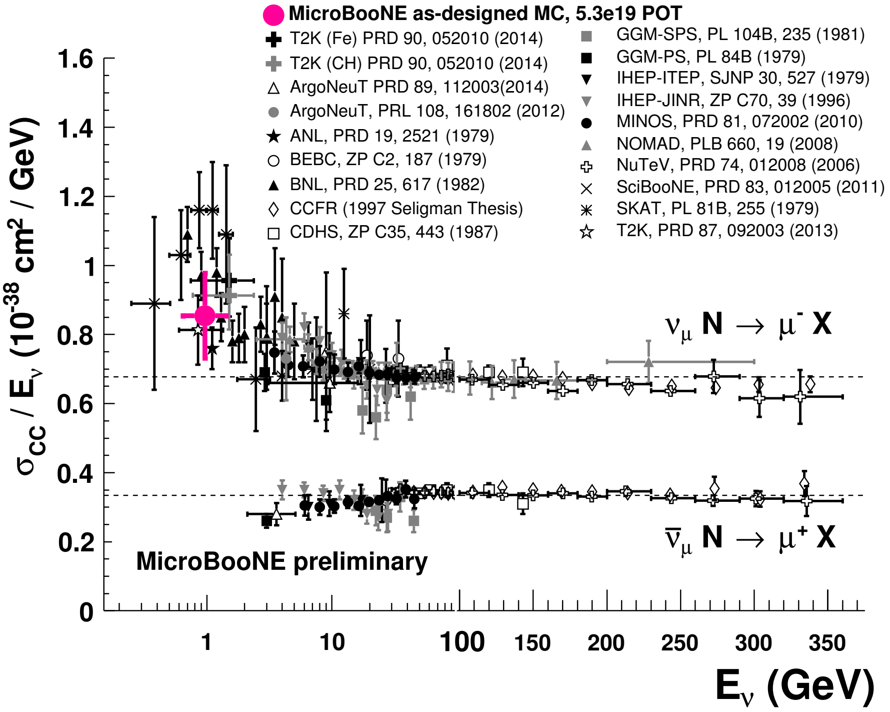

Figure 2: MicroBooNE flux-integrated ν_μ CC cross section prediction derived from an as-designed detector MC compared to other data[9].

6 Results

Using the equations shown above, the total flux integrated cross section results in

$$\sigma^{\text{MC}}_{(\text{as designed})} = \left[0.854 \pm 0.018 \text{ (stat.)} \pm 0.117 \text{ (sys.)}\right] \times 10^{-38} \text{ cm}^2. \qquad (3)$$

This is in agreement with the GENIE prediction, which is 0.84×10^{-38} cm^2, when integrating the cross section spline weighted with the BNB flux spectrum. The MicroBooNE flux-integrated cross section prediction is compared to other experiments in Figure 2.

Figure 3 shows the differential cross section result. As expected, the extracted data points follow the original GENIE simulation, which was used as input to this study.

7 Conclusions

This study estimates the performance of the MicroBooNE experiment for an initial ν_μ CC inclusive measurement using 5.3×10^{19} POT of BNB data (roughly 3 months of running at 1 Hz with 5×10^{12} POT per spill). The study is entirely

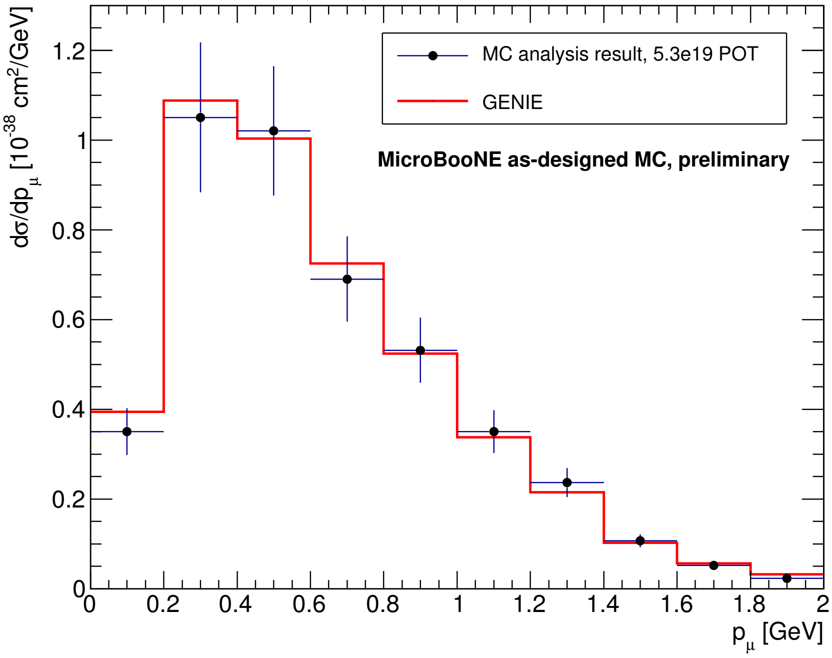

Figure 3: Differential cross section as a function of muon momentum. The MC points with uncertainties are the results extracted after event selection, background subtraction, unsmearing and efficiency correction, assuming an as-designed detector. The uncertainties contain statistical and systematic uncertainties. The red histogram is the prediction obtained directly from the original GENIE simulation, plotted as a function of true muon momentum.

based on the current LArSoft reconstruction and takes into account initial estimates for statistical and systematic uncertainties. The significance of the measurement predicted in this note is expected to improve with more statistics and improved reconstruction algorithms. However, the study is based on a detector simulation for MicroBooNE as it was designed, which is not reflecting the initial running conditions. Detector related effects not currently included in the simulation will affect the selection efficiency.

However, the result of this study shows that MicroBooNE will be able to deliver interesting results to the neutrino cross section community with only a few months of BNB data.

References

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