Charged Current Single Pion Cross Section Measurement at MiniBooNE

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We present MiniBooNE's preliminary $\nu_\mu$CC1$\pi^+$ cross section measurement, calculated using the ratio of CC1$\pi^+$ to CCQE events. We find the inclusive CC1$\pi^+$ measurement to be below the nuance\textsuperscript{1} and NEUGEN\textsuperscript{2} expectations.

1. Introduction

Charged current single pion (CC1$\pi^+$) production has been studied since the advent of high energy neutrino beams, but the cross section around 1 GeV energy is still not well understood. Also, many of the data that do exist come from hydrogen and deuterium targets, so there is still a significant need to study nuclear effects in this process. Figure 1\textsuperscript{3} shows a comparison of the CC1$\pi^+$ measurements from the Argonne\textsuperscript{4} and Brookhaven\textsuperscript{5} bubble chamber experiments, as well as the nuance\textsuperscript{1} Monte Carlo prediction for the CC1$\pi^+$ cross section.

The MiniBooNE CC1$\pi^+$ event sample is a semi-inclusive sample because the Cherenkov calorimeter detector is not able to resolve the final state recoil nucleons, and hence cannot distinguish the exclusive channels. In this work, we use the label CC1$\pi^+$ to indicate either of the resonant reactions, $\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- p \pi^+$ or $\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- n \pi^+$, as well as coherent pion production, $\nu_\mu A \rightarrow \mu^- A \pi^+$. A significant fraction of the CC1$\pi^+$ events at these energies are expected to arise from coherent production\textsuperscript{6}. Given the importance of CC1$\pi^+$ events as a background for $\nu_\mu \rightarrow \nu_e$ disappearance searches\textsuperscript{7}, the recent K2K SciBar limit on CC coherent pion production at 1.3 GeV\textsuperscript{8}, and the importance of coherent neutral current $\pi^0$ (NC$\pi^0$) production as a background source for $\nu_\mu \rightarrow \nu_e$ oscillation searches\textsuperscript{7}, there is significant interest in measuring the CC1$\pi^+$ cross section on carbon.

MiniBooNE\textsuperscript{9} is a neutrino oscillation experiment at Fermilab designed to confirm or rule out the hypothesis that the LSND $\bar{\nu}_e$ excess\textsuperscript{10} is due to $\nu_\mu \rightarrow \bar{\nu}_e$ oscillations. A general description of the experiment can be found elsewhere\textsuperscript{11}. CC1$\pi^+$ events are expected to comprise $\sim$25\% of the total MiniBooNE neutrino event rate, making these the second most probable interactions after charged current quasi-elastic (CCQE). For this reason they are interesting and useful for MiniBooNE. Prior measurements of these cross sections suffered from poor statistics\textsuperscript{12}. Sta-
tistical precision will not be a problem for Mini-BooNE; the MiniBooNE Monte Carlo, which uses the nuance neutrino generator [1], predicts that we should have almost 58,000 $\nu_\mu$ CC1$\pi^+$ events after cuts in the MiniBooNE detector with the full data set of $5.5 \times 10^{20}$ protons on target (POT).

1.1. Cross Section Ratio Overview

In this analysis, we normalize the observed rate of CC1$\pi^+$ events to that of CCQE events, and equate that to the ratio of CC1$\pi^+$ to CCQE cross sections. In doing this analysis, we use the fact that the same neutrino flux generates both event samples. Using the ratio allows us to neglect the uncertainties in the neutrino flux prediction. Moreover, if $\nu_\mu$ disappearance were present in the data, the predicted number of events in the Monte Carlo would be incorrect because of the depletion of the $\nu_\mu$ flux due to $\nu_\mu \rightarrow \nu_x$ oscillations. By normalizing to the CCQE data we avoid this issue.

We write the CC1$\pi^+$/CCQE cross section ratio as:

$$
\frac{\sigma_{CC1\pi^+}(E_\nu)}{\sigma_{CCQE}(E_\nu)} = \frac{N_{Data}^{CC1\pi+}(E_\nu)}{N_{Data}^{CCQE}(E_\nu)}. \tag{1}
$$

where $N_{Data}^{\alpha}$ is the true number of events of type $\alpha$ in the data. The true neutrino energy is denoted by $E_\nu$. If we assume that the CCQE cross section is well simulated by the Monte Carlo, then we may rewrite Equation 1:

$$
\sigma_{CC1\pi^+}(E_\nu) = \frac{N_{Data}^{CC1\pi+}(E_\nu)}{N_{Data}^{CCQE}(E_\nu)} \times \sigma_{MC}^{CCQE}(E_\nu). \tag{2}
$$

and thus obtain the CC1$\pi^+$ cross section measurement as a function of neutrino energy.

The raw event ratio is measured in the Monte Carlo as:

$$
R_{raw}^{MC}(E_{\nu}^{REC}) = \frac{N_{MC}^{afterCC1\pi^+cuts}(E_{\nu}^{REC})}{N_{MC}^{afterCCQEcuts}(E_{\nu}^{REC})}, \tag{3}
$$

where we have used $E_{\nu}^{REC}$ to denote the reconstructed energy of events from either process. To equate this to the cross section ratio, we must account for energy smearing, cut efficiencies, and the presence of background events in each data sample. We use the Monte Carlo to estimate each of these factors, and apply the derived corrections to the data samples before equating the event ratio to the cross section ratio.

### 2. CC1$\pi^+$ Event Analysis

MiniBooNE’s CC1$\pi^+$ event selection requires the simple yet robust cut of two Michel electrons following the neutrino interaction [13]. Approximately 40% of pions emitted at these energies stop in the detector oil. These decay to muons ($\mu^+$) with lifetime $\tau = 2.6 \times 10^{-8}$ ns, which then decay to Michel electrons. The muons ($\mu^-$) emitted from the neutrino interaction also come to rest, and 92% of these decay to Michel electrons.

Applying this requirement to $3.3 \times 10^{20}$ POT of MiniBooNE data yields over 44,000 CC1$\pi^+$ candidate events, making this data set larger by a factor of five than all previous CC1$\pi^+$ bubble chamber data published to date. The Monte Carlo predictions indicate that the event selection...
including light generated by the reconstructed ring; this is done to avoid in-
muon energy using only the Cherenkov light in produced by the
rection, and photon flux from the Cherenkov ring
fitter to the PMT hits to find the position, di-
under simple assumptions: we apply a single ring
cuts are \( \sim 30\% \) efficient for CC1\( \pi^+ \) events within the fiducial radius of 500 cm, with a purity of 85\%. Table 1 shows the fractions of signal and background events passing the CC1\( \pi^+ \) event sele-
tion. The background events come from either events with multiple pions that lose one or more of them within the nucleus, or CCQE events that acquire a \( \pi^+ \) though hadronic interactions within the nucleus, so that the events contain a single \( \mu^- \) and \( \pi^+ \) in the final state.

The CC1\( \pi^+ \) events are currently reconstructed under simple assumptions: we apply a single ring fitter to the PMT hits to find the position, di-
rection, and photon flux from the Cherenkov ring produced by the \( \mu^- \) in the event. This yields the muon energy using only the Cherenkov light in the reconstructed ring; this is done to avoid including light generated by the \( \pi^+ \) in calculating the muon energy. We then use the fitted energy and direction of the muon to reconstruct the neutrino energy by assuming the CC1\( \pi^+ \) reaction is a simple two body collision, e.g. \( \nu_\mu p \rightarrow \mu^- \Delta^{++} \).

Then we write the neutrino energy as:

\[
E_\nu^{REC} = \frac{1}{2} \frac{2m_\mu E_\mu - m_\mu^2 + (m_\Delta^2 - m_\mu^2)}{m_p - E_\mu + \cos \theta_\mu \sqrt{E_\mu^2 - m_\mu^2}}.
\]

where \( m_p \) is the proton mass, \( m_\mu \) is the muon mass, \( m_\Delta \) is the mass of the recoil resonance (which we take to be exactly 1232 MeV), and \( E_\mu \) and \( \theta_\mu \) are the reconstructed energy and angle of the outgoing muon.

Figure 2 shows the fraction of CC1\( \pi^+ \) events as a function of reconstructed neutrino energy, for both data and Monte Carlo. The data are shown as black points, with error bars representing the statistical uncertainties. The Monte Carlo results are shown as yellow points, with yellow error bands representing the systematic uncertainties. Monte Carlo studies indicate that the neutrino energy resolution is about 20\%. Much of the resolution comes from the assumption that the recoil resonance has mass equal to 1232 MeV; however MiniBooNE is not able to reconstruct the invariant mass of the \( \Delta \) because the emitted nucleon does not leave a Cherenkov ring. The CC1\( \pi^+ \) Monte Carlo predictions are based on the Rein and Sehgal model for resonant and coherent pion production \[9\][13], and the nuance nuclear model \[1\].

The Michel electrons from the CC1\( \pi^+ \) candidate events are used to verify the composition of the data set. The \( \mu^- \) are captured by carbon nuclei with a probability of 8\%, changing the lifetime to 2026.3±1.5 ns \[14\] from the expected 2197.03±0.04 ns \[13\]. The distance from each reconstructed Michel to the end of the \( \mu^- \) track is calculated, the Michaels are sorted into “close” and “far” samples based on the distance to the end of the \( \mu^- \) track. The lifetimes for the two samples are shown in Fig. 3. The observed muon lifetimes for the close and far Michel samples are 2057±14 ns and 2218±15 ns, respectively, indi-

![Figure 3. Distribution of muon lifetimes from charged current single pion events. Only data are shown, with only statistical errors.](image)

| Reaction Type         | Percentage |
|-----------------------|------------|
| resonant CC1\( \pi^+ \)| 75.8\%     |
| coherent CC1\( \pi^+ \)| 9.2\%      |
| CC QE                 | 4.1\%      |
| multi-pion            | 6.1\%      |
| DIS                   | 2.6\%      |
| CC\( \pi^0 \)         | 1.5\%      |
| other                 | 0.7\%      |

Table 1: Event composition of CC1\( \pi^+ \) sample.
cating that they are indeed mostly from $\mu^-$ and $\mu^+$ decay, respectively. The same studies performed on the Monte Carlo events yield lifetimes of $2043 \pm 15$ ns and $2203 \pm 15$ ns, and show that the close and far samples are $\sim 80\%$ pure $\mu^-$ and $\mu^+$, respectively.

3. CC QE Event Selection

The CCQE event reconstruction is described in greater detail elsewhere [17]. To summarize, the event selection uses a 10 variable Fisher discriminant designed to find a single Cherenkov ring from a muon. The neutrino energy is reconstructed using simple two-body kinematics and corrected for the effects of Fermi momentum of the target nucleon. Figure 4 shows the fraction of CCQE events as a function of reconstructed neutrino energy, for both data and Monte Carlo. The data are shown as black points, with error bars representing the statistical uncertainties. The Monte Carlo results are shown as yellow points, with yellow error bands representing the systematic uncertainties.

Applying the CCQE event selection to $2.3 \times 10^{20}$ POT of MiniBooNE data yields over 60k CCQE events, with 86% purity. Table 2 shows the fractions of signal and background events passing the CCQE event selection. The background events come mostly from single pion events in which the pion is absorbed within the nucleus, so that the events contain a single $\mu^-$ and no $\pi$ in the final state.

4. CC1$\pi^+$ Cross Section

To use Equation 2 to calculate the cross section, we first calculate the ratio of CC1$\pi^+$/CCQE events. The numerator of the ratio is the event sample shown in Figure 2 after it was corrected for the background fraction, energy smearing and cut efficiencies. Similarly, the denominator is shown in Figure 4. The ratio of CC1$\pi^+/CCQE$ events as a function of neutrino energy is shown in Figure 5. Note that this neutrino energy has been corrected for energy smearing. The error bars show the systematic uncertainties added in quadrature with the statistical uncertainties.

We restrict the analysis to the reconstructed energy region 0.5 GeV-1.4 GeV. This is because the CC1$\pi^+$ sample has insufficient statistics below $\sim 0.5$ GeV, due to the energy threshold for $\Delta$ production, and the CCQE sample has insufficient statistics above $\sim 1.4$ GeV, due to the efficiency of the event selection cuts for high muon energies.

To calculate the CC1$\pi^+$ cross section, we multiply the ratio by the Monte Carlo CCQE prediction. The Monte Carlo prediction is based on the nuance neutrino generator, which assumes a Llewellyn-Smith quasi-elastic cross section [18], and a Smith-Moniz Fermi gas model for nuclear interactions [19]. The nuance program also simulates final state interactions, which mainly include the interaction probabilities of the final state particles while they are still inside the nucleus [1]. The MiniBooNE Monte Carlo uses the BBA03 non-dipole vector form factors [20], and a dipole axial form factor with $M_A=1.03$.

Figure 6 shows MiniBooNE’s CC1$\pi^+$ cross section measurement. Again, the data are shown as black points, with statistical error bars. The yellow error bands represent the present estimate of the systematic uncertainties. Also shown are the nuance and NEUGEN [2] predictions for the CC1$\pi^+$ cross section. Although the CC1$\pi^+$ mea-
measurement is calculated from the ratio with the nuance CCQE cross section, the comparison to NEUGEN is appropriate because its CCQE prediction is identical to the nuance prediction.

Note that the MiniBooNE CC1π measurement lies ∼25% below the nuance and NEUGEN predictions. One plausible explanation for this apparent disparity is offered by Figure 4 the ANL and BNL measurements of the νp → μ−pπ+ cross section. The BNL measurement lies ∼40% above the ANL, and nuance splits the difference. MiniBooNE’s measurement lying 25% below the nuance prediction suggests that it is more consistent with the ANL observation.

5. Systematic Uncertainties

The sources of systematic error considered here are summarized in Table 3 and can be generally categorized as neutrino cross section, optical model, and energy scale uncertainties. By optical model, we mean the properties of light generation and transmission in the detector mineral oil.

The systematic uncertainties are assessed on the CC1π+/CCQE ratio, so there is some cancellation of errors.

We include cross section uncertainties in a cross section measurement because we must assess the error on the predicted number of events which pass the CCQE selection cuts. The CCQE background after cuts is dominantly from CC1π+ events, and so any normalization uncertainty on the predicted CC1π+ (and CCQE) event rates must be included. Second, efficiency corrections are applied to the CC1π+ data which are derived from the Monte Carlo, and so any energy dependent uncertainties must be included.

The cross section uncertainties are all derived from external data [21]. The optical model uncertainties are derived from “table-top” measurements of the oil and in situ calibration data samples [22]. The correlations between the sources of uncertainty are not yet fully determined, so we
Figure 6. Semi-inclusive CC1π+ cross section vs. neutrino energy, extracted assuming the nuance CCQE cross section prediction with $M_{A}^{QE} = 1.03$ GeV. Statistical uncertainties are shown by the black error bars, and the important contributions to the systematic uncertainties are shown by the yellow error bands. Also shown are the nuance and NEUGEN predictions for the semi-inclusive CC1π+ cross section vs. reconstructed neutrino energy.

present the analysis assuming they are all uncorrelated, adding all uncertainties in quadrature. In fact, we expect many of the sources of uncertainty to be anti-correlated.

6. Conclusions

We have presented the first measurement of the semi-inclusive $\nu_\mu$CC1π+ cross section ratio on a nuclear target near 1 GeV. From this, we extract a CC1π+ cross section measurement which is lower than the predictions of the nuance and NEUGEN Monte Carlos, but appears consistent with the ANL observation of resonant single pion production.

| Source          | Effect on $\sigma$ |
|-----------------|--------------------|
| Optical Model   | 20%                |
| Cross Sections  | 15%                |
| Energy Scale    | 10%                |
| Statistics      | 6%                 |

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