FERMILAB-CONF-06-040-E

Charged Current Single Pion Cross Section Measurement at MiniBooNE

M.O. Wascko[a], for the MiniBooNE Collaboration

[a]Department of Physics and Astronomy,
Louisiana State University, Baton Rouge, LA 70803

We present MiniBooNE's preliminary ν_μCC1π^+ cross section measurement, calculated using the ratio of CC1π^+ to CCQE events. We find the inclusive CC1π^+ measurement to be below the `nuance` [1] and NEUGEN [2] expectations.

1. Introduction

Charged current single pion (CC1π^+) 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 [3] shows a comparison of the CC1π^+ measurements from the Argonne [4] and Brookhaven [5] bubble chamber experiments, as well as the `nuance` [1] Monte Carlo prediction for the CC1π^+ cross section.

The MiniBooNE CC1π^+ 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 CC1π^+ to indicate either of the resonant reactions, $\nu_\mu p \to \mu^-\Delta^{++} \to \mu^- p\pi^+$ or $\nu_\mu n \to \mu^-\Delta^+ \to \mu^- n\pi^+$, as well as coherent pion production, $\nu_\mu A \to \mu^- A\pi^+$. A significant fraction of the CC1π^+ events at these energies are expected to arise from coherent production [6]. Given the importance of CC1π^+ events as a background for $\nu_\mu \to \nu_x$ disappearance searches [7], the recent K2K SciBar limit on CC coherent pion production at 1.3 GeV [8], and the importance of coherent neutral current π^0 (NCπ^0) production as a background source for $\nu_\mu \to \nu_e$ oscillation searches [7], there is significant interest in measuring the CC1π^+ cross section on carbon.

MiniBooNE [9] is a neutrino oscillation experiment at Fermilab designed to confirm or rule out the hypothesis that the LSND $\bar{\nu}_e$ excess [10] is due to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. A general description of the experiment can be found elsewhere [11]. CC1π^+ events are expected to comprise ~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 [12]. Statistical precision will not be a problem for MiniBooNE; the MiniBooNE Monte Carlo, which uses

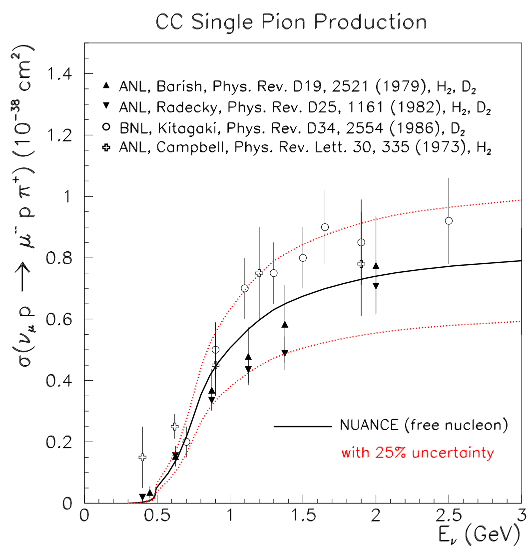

Figure 1. *Previous measurements of the total cross section per nucleon of the process $\nu_\mu p \to \mu^- p\pi^+$ at low neutrino energy.*

the `nuance` neutrino generator [1], predicts that we should have almost 58,000 ν_μCC1π^+ 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 CC1π^+ events to that of CCQE events, and equate that to the ratio of CC1π^+ to CCQE cross sections. In doing the analysis this way, 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 ν_μ disappearance were present in the data, the predicted number of events in the Monte Carlo would be incorrect because of the depletion of the ν_μ flux due to $\nu_\mu \rightarrow \nu_x$ oscillations. By normalizing to the CCQE data we avoid this issue.

We write the CC1π^+/CCQE cross section ratio as:

$$\frac{\sigma_{CC1\pi}(E_\nu)}{\sigma_{CCQE}(E_\nu)} = \frac{N^{Data}_{CC1\pi}(E_\nu)}{N^{Data}_{CCQE}(E_\nu)}, \quad (1)$$

where N^{Data}_α is the true number of events of type α in the data. The true neutrino energy is denoted by E_ν. If we assume that the CCQE cross section is well simulated by the Monte Carlo, then we may rewrite Equation 1:

$$\sigma_{CC1\pi}(E_\nu) = \frac{N^{Data}_{CC1\pi}(E_\nu)}{N^{Data}_{CCQE}(E_\nu)} \times \sigma^{MC}_{CCQE}(E_\nu), \quad (2)$$

and thus obtain the CC1π^+ cross section measurement as a function of neutrino energy.

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

$$R^{MC}_{raw}(E^{REC}_\nu) = \frac{N^{MC}_{afterCC1\pi cuts}(E^{REC}_\nu)}{N^{MC}_{afterCCQEcuts}(E^{REC}_\nu)}, \quad (3)$$

where we have used E^{REC}_ν 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.

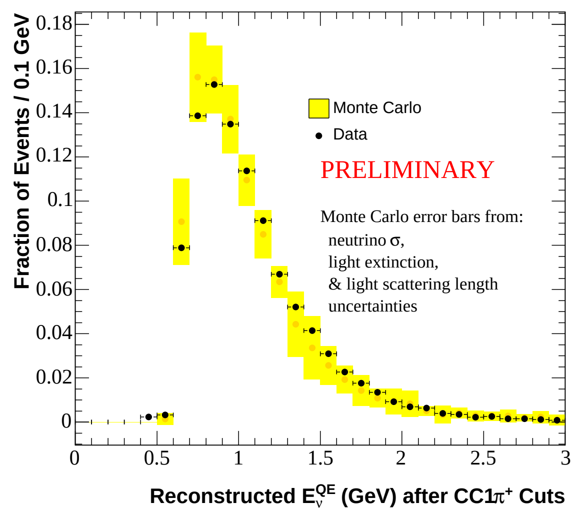

Figure 2. *Distribution of events versus reconstructed neutrino energy, for events passing* CC1π^+ *cuts. Black points show data with statistical errors. Monte Carlo results are shown in yellow, with error bars showing some important contributions to the systematic uncertainties. Data and Monte Carlo are normalized to unit area.*

2. CC1π^+ Event Analysis

MiniBooNE's CC1π^+ 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 (μ^+) with lifetime $\tau = 2.6 \times 10^{-8}$ ns, which then decay to Michel electrons. The muons (μ^-) 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 CC1π^+ candidate events, making this data set larger by a factor of five than all previous CC1π^+ bubble chamber data published to date. The Monte Carlo predictions indicate that the event selection cuts are $\sim$30% efficient for CC1π^+ 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 CC1π^+ event selection. The background events come from either events with multiple pions that lose one or more

Table 1
Event composition of CC1π^+ *sample.*

Reaction Type	Percentage
resonant CC1π^+	75.8%
coherent CC1π^+	9.2%
CC QE	4.1%
multi-pion	6.1%
DIS	2.6%
CCπ^0	1.5%
other	0.7%

of them within the nucleus, or CCQE events that acquire a π^+ though hadronic interactions within the nucleus, so that the events contain a single μ^- and π^+ in the final state.

The CC1π^+ events are currently reconstructed under simple assumptions: we apply a single ring fitter to the PMT hits to find the position, direction, and photon flux from the Cherenkov ring produced by the μ^- 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 π^+ in calculating the muon energy. We then use the fitted energy and direction of the muon to reconstruct the neutrino energy by assuming the CC1π^+ reaction is a simple two body collision, e.g. $\nu_\mu p \rightarrow \mu^- \Delta^{++}$. Then we write the neutrino energy as:

$$E_\nu^{REC} = \frac{1}{2}\frac{2m_p E_\mu - m_\mu^2 + (m_\Delta^2 - m_p^2)}{m_p - E_\mu + \cos\theta_\mu \sqrt{E_\mu^2 - m_\mu^2}}, \qquad (4)$$

where m_p is the proton mass, m_μ is the muon mass, m_Δ is the mass of the recoil resonance (which we take to be exactly 1232 MeV), and E_μ and θ_μ are the reconstructed energy and angle of the outgoing muon.

Figure 2 shows the fraction of CC1π^+ 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;

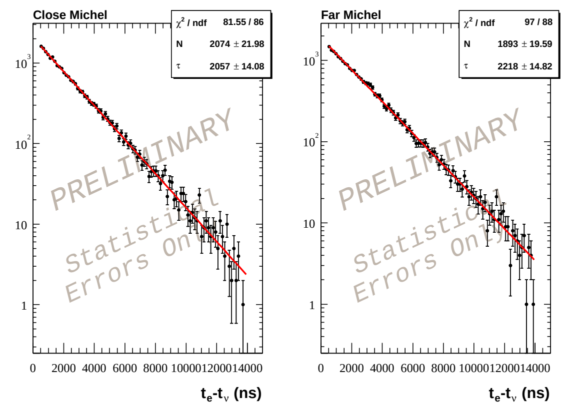

Figure 3. *Distribution of muon lifetimes from charged current single pion events. Only data are shown, with only statistical errors.*

however MiniBooNE is not able to reconstruct the invariant mass of the Δ because the emitted nucleon does not leave a Cherenkov ring. The CC1π^+ Monte Carlo predictions are based on the Rein and Sehgal model for resonant and coherent pion production [6][14], and the `nuance` nuclear model [1].

The Michel electrons from the CC1π^+ candidate events are used to verify the composition of the data set. The μ^- are captured by carbon nuclei with a probability of 8%, changing the lifetime to 2026.3±1.5 ns [15] from the expected 2197.03±0.04 ns [16]. The distance from each reconstructed Michel to the end of the μ^- track is calculated, the Michels are sorted into "close" and "far" samples based on the distance to the end of the μ^- 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, indicating that they are indeed mostly from μ^- and μ^+ decay, respectively. The same studies performed on the Monte Carlo events yield lifetimes of 2043±15 ns and 2203±15 ns, and show that the close and far samples are ∼80% pure μ^- and μ^+, repectively.

Table 2
Event composition of CCQE sample.

Reaction Type	Percentage
CCQE	86.0%
$CC1\pi^+$: resonant	8.9%
$CC1\pi^+$: coherent	1.4%
$NC1\pi^+$	1.7%
$CC1\pi^0$	1.1%
$CC\pi^0$	1.5%
other	0.9%

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 2.3×10^{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 μ^- and no π in the final state.

Monte Carlo studies indicate that the neutrino energy resolution is about 10%. This is better than the $CC1\pi^+$ energy resolution because the mass of the recoil particle (a proton) is well known, and the muon Cherenkov ring is cleaner because there is no π^+ 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

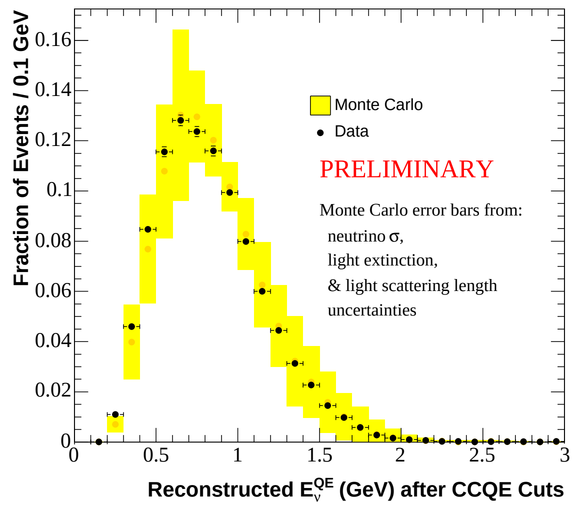

Figure 4. *Distribution of events versus reconstructed neutrino energy for events passing CCQE cuts. Black points show data with statistical errors. Monte Carlo results are shown in yellow, with error bars showing some important contributions to the systematic uncertainties. Data and Monte Carlo are normalized to unit area.*

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 Δ 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

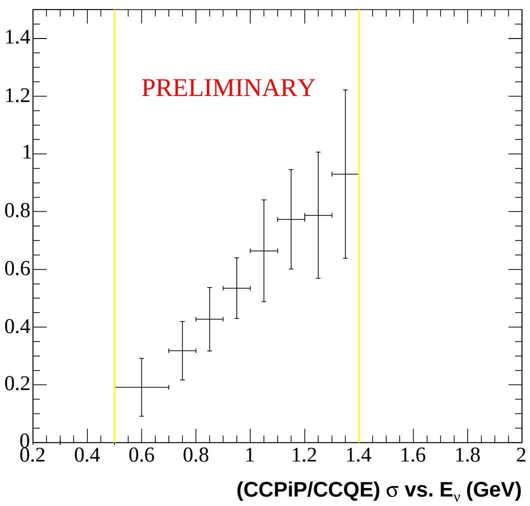

Figure 5. *Ratio of* CC1π^+*/CCQE events vs. neutrino energy, after corrections for background events, energy smearing, and cut efficiencies. The black error bars show the statistical and systematic uncertainties added in quadrature.*

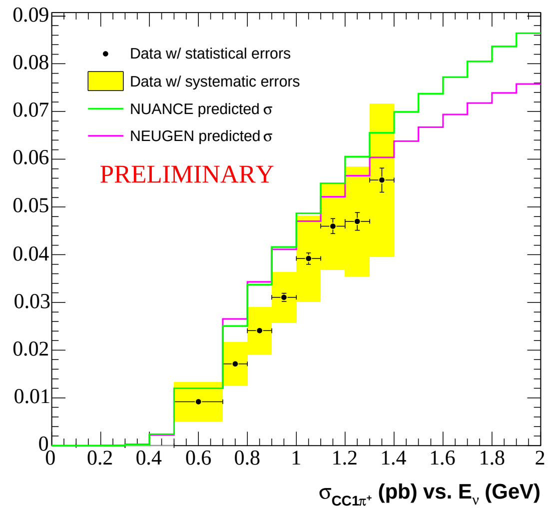

Figure 6. *Semi-inclusive* CC1π^+ *cross section vs. neutrino energy, extracted assuming the* `nuance` *CCQE cross section prediction with* M_A^{QE}*=1.03 GeV. Statistical uncertainties are shown by the black error bars, and the important contributions to the systematic uncertainties are shown by the yellow error bands. Also shown are the* `nuance` *and NEUGEN predictions for the semi-inclusive* CC1π^+ *cross section vs. reconstructed neutrino energy.*

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 CC1π^+ 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 CC1π^+ cross section. Although the CC1π^+ 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 1: the ANL[4] and BNL[5] measurements of the $\nu_\mu p \rightarrow \mu^- p \pi^+$ 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

Table 3
Sources of uncertainty considered for the $CC1\pi^+$ cross section analysis, summed over the entire analysis region from 0.5 to 1.4 GeV.

source	*effect on* σ
Optical Model	20%
Cross Sections	15%
Energy Scale	10%
Statistics	6%

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 $CC1\pi^+$ events, and so any normalization uncertainty on the predicted $CC1\pi^+$ (and CCQE) event rates must be included. Second, efficiency corrections are applied to the $CC1\pi^+$ 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 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 $\nu_\mu CC1\pi^+$ cross section ratio on a nuclear target near 1 GeV. From this, we extract a $CC1\pi^+$ 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.

7. Acknowledgments

The author is pleased to acknowledge collaboration with J. Monroe in this analysis, and would also like to express gratitude to the organizers of NuInt05 for their generous travel support.

The MiniBooNE collaboration gratefully acknowledges support from the Department of Energy and the National Science Foundation. The author was supported by grant number DE-FG02-91ER0617 from the Department of Energy.

REFERENCES

1. D. Casper, Nucl. Phys. Proc. Suppl. **112**, 161 (2002), *hep-ph/0208030*.
2. H. Gallagher, Nucl. Phys. Proc. Suppl. **112** (2002) 188.
3. G. P. Zeller, private communication.
4. S. J. Barish *et al.*, Phys. Rev. D **19**, 2521 (1979,)G. M. Radecky *et al.* Phys. Rev. D **25**, 1161 (1982.)
5. T. Kitagaki *et al.*, Phys. Rev. D **34**, 2554 (1986).
6. D. Rein and L. M. Sehgal, Ann. Phys. 133 (1981) 79 .
7. K. Hiraide, "The SciBooNE Experiment," these proceedings.
8. M.Hasegawa *et al.*, Phys. Rev. Lett. **95**, 2005 (252301).
9. FERMILAB-PROPOSAL-0898, Dec 1997, *nucl-ex/9706011* .
10. A. Aguilar *et al.*,Phys. Rev. D, 64, 2001, *hep-ex/0104049*.
11. A. A. Aguilar-Arevalo *et al.*, "The MiniBooNE Run Plan" (2003).
12. G. P. Zeller, NuInt02, *hep-ex/0312061*.
13. M. O. Wascko, DPF04, *hep-ex/0412008*.
14. D. Rein and L. M. Sehgal, Nucl. Phys. **B223**, 29 (1983).
15. S.Eidelman *et al.*, Phys. Lett. **B592**, 33 (2004).
16. T.Suzuki *et al.*, Phys. Rev. **C35**, 2122 (1987).
17. J. Monroe, Moriond 2004, *hep-ex/0406048*.
18. C. Llewellyn-Smith, Phys. Rept. C3 (1972) 261 .
19. R. A. Smith and E. J. Moniz, Nucl. Phys. B 43 (1972) 605. [Erratum-ibid. B 101 (1975) 547].
20. H. Budd *et al.*, *hep-ex/0308005*, *hep-ex/0309024* .
21. E. A. Hawker, Nucl. Phys. Proc. Suppl. 139, 260 (2005).
22. B. C. Brown, FERMILAB-CONF-04-282-E