

Measurement of the neutrino component of an anti-neutrino beam observed by a non-magnetized detector

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Two independent methods are employed to measure the neutrino flux of the anti-neutrino-mode beam observed by the MiniBooNE detector. The first method compares data to simulated event rates in a high purity ν_μ induced charged-current single π^+ (CC1 π^+) sample while the second exploits the difference between the angular distributions of muons created in ν_μ and $\bar{\nu}_\mu$ charged-current quasi-elastic (CCQE) interactions. The results from both analyses indicate the prediction of the neutrino flux component of the pre-dominately anti-neutrino beam is over-estimated - the CC1 π^+ analysis indicates the predicted ν_μ flux should be scaled by 0.76 ± 0.11 , while the CCQE angular fit yields 0.65 ± 0.23 . The energy spectrum of the flux prediction is checked by repeating the analyses in bins of reconstructed neutrino energy, and the results show that the spectral shape is well modeled. These analyses are a demonstration of techniques for measuring the neutrino contamination of anti-neutrino beams observed by future non-magnetized detectors.

I. INTRODUCTION

If θ_{13} is non-zero, next generation neutrino oscillation experiments will embark on a program to measure the neutrino mass ordering and look for evidence of CP violation in the neutrino sector. This effort will require precise oscillation measurements with both neutrino and anti-neutrino beams in order to isolate these effects. Since beams produced in an accelerator environment are never

purely neutrino nor anti-neutrino in content, detectors must be able to separate the two contributions. Most commonly, this is achieved by employing a magnetic field to identify the final-state μ^- (or μ^+) produced in charged-current ν_μ (or $\bar{\nu}_\mu$) interactions. A handle on the overall level and energy dependence of ν_μ versus $\bar{\nu}_\mu$ induced events, however, is also possible in unmagnetized detectors with a suitable choice of reaction channels.

Accelerator-based neutrino beams are typically created by colliding proton beams with thick nuclear targets. Mesons produced at a variety of energies and angles are focused by a magnetic horn before entering a decay tunnel. Meson decays can be calculated sufficiently well for a given beam geometry that the neutrino flux uncertainties arise mainly from uncertainties in the meson production cross sections. In particular, to avoid extrapolating data

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taken with diverse nuclear target materials or proton energies, neutrino experiments require dedicated hadron production cross-section measurements taken with the same beam energy and target to obtain a reliable flux prediction. If an accelerator-based neutrino experiment lacks such hadron production data, it may be able to meet its oscillation analysis goals using calibrations from a near detector; however the secondary physics goal of measuring neutrino-nucleon absolute cross sections will still be limited by flux uncertainties.

To avoid ambiguity, in this paper references to “neutrinos” are not meant to also refer to anti-neutrinos, and “mode” refers to the polarity of the magnetic focusing horn used in the beamline. In this way, for example, “anti-neutrino events” refers to anti-neutrino induced events exclusively while “anti-neutrino-mode events” refers to data obtained when the horn polarity focuses negatively charged particles, which is a mix of neutrino and anti-neutrino induced events.

The Mini Booster Neutrino Experiment (MiniBooNE) is located at Fermilab in Batavia, Illinois and has made many oscillation [1–5] and cross section [6–13] measurements. For MiniBooNE, the pion production data crucial to the flux model come from cross sections reported by the HARP experiment [14]. However, even with dedicated data appropriate to the experimental setup of MiniBooNE, there remain small regions of phase space relevant to MiniBooNE not covered by the HARP measurements. Of particular importance is the production of very forward pions with respect to the direction of the incoming proton beam. This is the dominant production region of parent particles contributing neutrinos to the anti-neutrino-mode beam, or vice versa. MiniBooNE uses a magnetic horn to defocus the majority of these background parent particles, but as Figure 1 suggests, the very forward pions can escape magnetic deflection. This same angular region suffers from re-interactions in the target and a severe proton background, preventing a clean measurement of the pion production cross section. For these reasons, pion cross sections in the $\theta_\pi < 30$ mrad region, where θ_π is the angle the outgoing pion makes with respect to the incoming proton beam, are not reported by HARP and the majority of the MiniBooNE flux prediction arising from π^+ (π^-) decay while focusing π^- (π^+) is extrapolated from the available hadron production data. The hadron production data cover $\sim 90\%$ of sign selected pions, while less than 25% of oppositely charged pions in the same beam are constrained.

The overall contamination rate is more significant in anti-neutrino mode due to effects from both flux and cross section: the leading-particle effect at the target preferentially produces about twice as many π^+ as π^- , and the neutrino cross section is about three times higher than the anti-neutrino cross section in the MiniBooNE energy range (~ 1 GeV) [15]. For these reasons anti-neutrino induced events are not a serious complication for neutrino-mode running, as these flux and cross-section effects conspire to suppress their contribution, while the

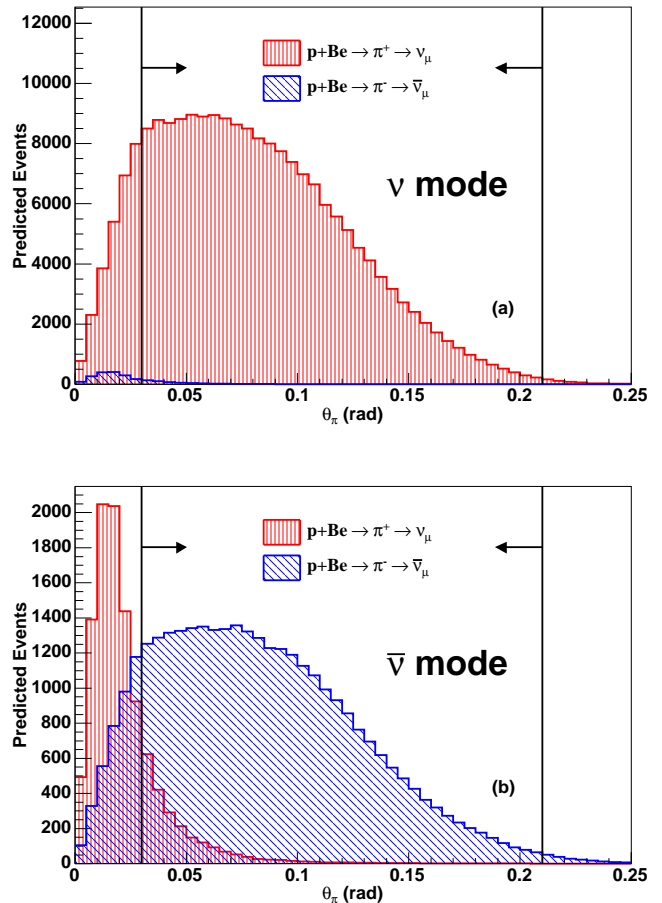


FIG. 1: (Color online) Predicted angular distributions of pions with respect to the incident proton beam (θ_π) producing ν_μ and $\bar{\nu}_\mu$ in (a) neutrino mode and (b) anti-neutrino mode. Only pions leading to ν_μ and $\bar{\nu}_\mu$ events in the detector are shown, and all distributions are normalized to 5.66×10^{20} protons on target. Arrows indicate the region where HARP data [14] are available.

same effects amplify the neutrino contamination in anti-neutrino-mode data. Simulation predicts anti-neutrino events account for $\sim 1\%$ of neutrino-mode data while neutrinos are responsible for $\sim 30\%$ of anti-neutrino-mode data. This motivates a dedicated study of the neutrino flux contribution to the anti-neutrino-mode data. A data set corresponding to 5.66×10^{20} protons on target is analyzed here and is important for both the ongoing MiniBooNE anti-neutrino oscillation search [4, 5] and anti-neutrino cross-section measurements.

Two independent approaches for measuring the neutrino flux in anti-neutrino-mode are taken. In the first method, a high purity sample of charged-current single π^+ ($CC1\pi^+$) events isolate the ν_μ contribution in the beam. The second method exploits the interference term in the charged-current quasi-elastic (CCQE) cross section, where the angular distribution of final-state muons

are predicted to be distinct for ν_μ compared to $\bar{\nu}_\mu$ interactions. Both techniques were introduced in the MiniBooNE anti-neutrino-mode run proposal [16]. These two approaches offer complementary means of measuring the neutrino flux component in anti-neutrino-mode data, with the CCQE sample providing a constraint at lower neutrino energies while the $\text{CC}1\pi^+$ measurement covers higher energies. They provide both a check of the MiniBooNE beam simulation in a region not covered by external data and demonstrate a set of techniques for measuring the ν_μ contamination in an anti-neutrino-mode beam in the absence of a magnetized detector. It has been argued elsewhere that even modest statistical separation of charged-current neutrino and anti-neutrino events, afforded by the kind of analyses presented here, may be sufficient to meet the physics goals in proposed future experiments such as neutrino factories [17].

This paper is organized as follows: the MiniBooNE experiment is described in Section II while Section III details the neutrino and anti-neutrino scattering models. Two independent measurements of the neutrino contribution to the anti-neutrino flux are presented in Sections IV and V. The results are compared in Section VI, implications for other neutrino experiments are discussed in Section VII and this work is summarized in Section VIII.

II. THE MINIBOONE EXPERIMENT

A. Beamline and flux

The Booster Neutrino Beamline (BNB) provides the neutrino and anti-neutrino flux to MiniBooNE. A beam of 8 GeV kinetic energy protons is extracted from the Booster synchrotron in “spills” of 5×10^{12} protons over 1.6 μs at a maximum rate of 5 Hz. A lattice of alternatively focusing and defocusing quadrupole magnets steer the proton bunches to a beryllium target 71 cm (1.75 interaction lengths) long. The protons collide with the target to create a spray of secondary particles. An aluminum electromagnetic horn surrounding the target is pulsed to coincide with the p-Be collisions, creating a toroidal magnetic field to focus mesons of the desired charge. The horn pulses are such that the magnetic field is constant for the duration of the proton spill. In neutrino mode, the magnetic horn focuses positively charged secondary particles while defocusing those with negative charge; the horn effects are reversed in anti-neutrino mode. The focused mesons are allowed to decay in a 50 m air-filled decay region which terminates at a steel beam dump. The dominant decay modes of the mesons, mostly pions, produce muon neutrinos and anti-neutrinos.

A GEANT4-based model [18] is used to predict the neutrino and anti-neutrino flux at the detector. The simulation considers proton travel to the target, p-Be interactions in the target including meson production, magnetic horn focusing, particle propagation, meson decay, and finally neutrino and anti-neutrino transport to the

detector. As mentioned earlier, measurement of pion cross sections from p-Be interactions are obtained from the HARP experiment. The HARP double differential cross-section error matrix is used to set pion production uncertainties [19]. Even with valuable data constraints, meson production at the target contributes the largest systematic error to the flux prediction. The fractional uncertainty on pion production is $\sim 8\%$ around the flux peak, while the uncertainty grows significantly in regions dominated by pions unconstrained by HARP data. The flux prediction in neutrino and anti-neutrino modes is presented in Figure 2. Details of the beamline and flux prediction are given in Ref. [19].

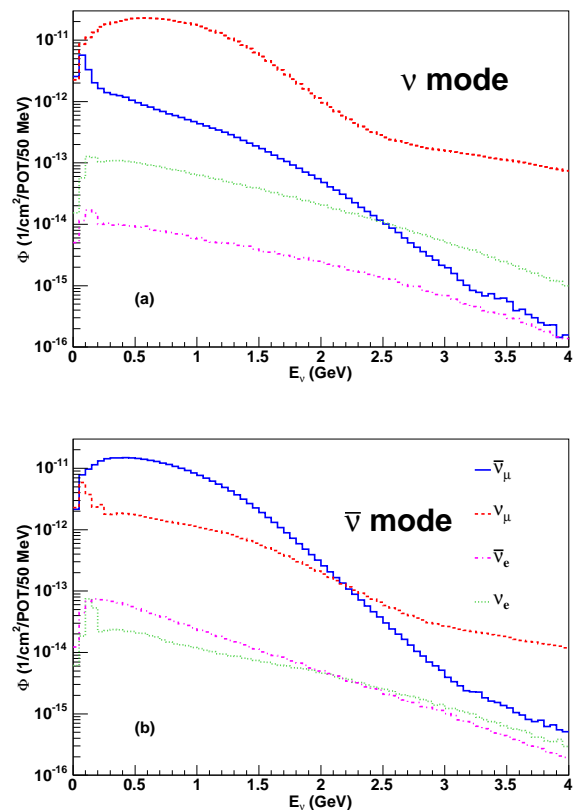


FIG. 2: (Color online) The MiniBooNE flux prediction for (a) neutrino mode and (b) anti-neutrino mode. Due to the leading-particle effect, the neutrino contribution to the anti-neutrino-mode flux is more significant compared to the anti-neutrino component of the neutrino-mode beam. Plots taken from Ref. [19].

B. Detector

The MiniBooNE detector is a 6.1 m radius sphere filled with 818 tons of pure Marcol7 mineral oil. It houses 1520 8-inch Hamamatsu photomultiplier tubes (PMTs) segregated into two optically isolated regions: an inner

signal region of 575 cm radius and an outer veto shell of thickness 35 cm. The former contains 1280 PMTs (11.3% coverage) while the latter holds 240 PMTs. The veto region is used to enforce containment of charged particles produced by neutrinos and anti-neutrinos from the beam and reject charged particles entering the tank.

The mineral oil has a density of 0.845 g/cm³ with an index of refraction of 1.47 at 20 °C. Charged particles with velocity $\beta > 0.68$ produce Cherenkov radiation. Particle identification and reconstruction is principally obtained through the pattern and timing of this prompt Cherenkov light; however, delayed scintillation light present due to fluorescent components in the oil has also been used effectively to provide energy information for charged particles produced below Cherenkov threshold [10].

MiniBooNE electronics record PMT charge and time information beginning about 5 μ s before the 1.6 μ s BNB proton delivery. Data are recorded for a total of 19.2 μ s. The 5 μ s interval before the beam spill is primarily present to minimize data contamination caused by cosmic ray muons stopping in the signal region prior to the start of the DAQ window. PMT activity is recorded for more than 10 μ s after beam delivery to observe electrons from the at-rest decay of muons (hereafter referred to as “Michel” electrons) subsequent to the initial neutrino or anti-neutrino induced interaction.

The detector response to muons is measured using a dedicated muon tagging system that independently measures the energy and direction of cosmic ray muons up to 800 MeV. MiniBooNE employs a scintillator hodoscope directly above the detector and seven internal scintillator cubes at different depths, each connected to a dedicated one-inch PMT for readout. The measured ranges and directions of muons traversing the hodoscope and stopping in cubes are used to verify muon reconstruction algorithms. The energy (angle) resolution improves from 12% (5.4 deg) at 100 MeV to 3.4% (1.0 deg) at 800 MeV. Full detector details and calibrations are available in Ref. [20].

C. Detector simulation

The detector response to particle interactions and propagation is simulated using GEANT3 [21]. The entire detector geometry is considered, including the steel tank, external supports and main inner components. In addition, the surrounding environment composed of dirt external to the MiniBooNE enclosure, the concrete cylindrical housing and the air-filled gap between the detector and walls is treated. Of critical importance is the treatment of particle transport in the detector medium. The GEANT3 program takes as input the final-state particles emerging from the nucleus and simulates their propagation in the detector.

With a few exceptions, MiniBooNE uses the standard GEANT3 settings to simulate physics processes. Deviations include a custom model for light propagation in

the detector oil and a substitution of the hadronic interaction model. The default GFLUKA hadron model is replaced by the GCALE [22] package, which better models pion absorption ($\pi^\pm + X \rightarrow X'$) and charge exchange ($\pi^\pm + X \rightarrow \pi^0 + X'$) processes. This is particularly relevant for the present analysis, where the predicted event composition of the two interaction samples studied is dependent on the pion survival model. Based on comparisons with external data [23] and the GCALE prediction, an uncertainty of 35% (50%) is assigned to the pion absorption (charge exchange) interaction *in the detector medium*. The uncertainty for the same processes *inside the nucleus* is discussed in Section III C.

The model for light propagation in the oil is formed using a combination of external measurements and calibration data. Photon emission through Cherenkov and scintillation processes is simulated and propagated until the photon either is absorbed or hits a PMT photocathode, possibly leading to photoelectron production. Light emission, attenuation and scattering are included. The optical model of the detector describes the wavelength, time, and angular dependence of these processes [24].

III. PREDICTED NEUTRINO AND ANTI-NEUTRINO INTERACTIONS

MiniBooNE uses the NUANCE [15] event generator to simulate neutrino and anti-neutrino interactions in the detector. NUANCE includes a comprehensive neutrino and anti-neutrino cross section model which considers known interactions in the neutrino and anti-neutrino energy range from ~ 100 MeV to 1 TeV. Ninety-nine reactions are modeled separately and combined with nuclear models describing bound nucleon states and final-state interactions to predict event rates and kinematics.

Bound nucleons in the detector medium are described by the Relativistic Fermi Gas model [25]. This assumes the nucleons to be independent and quasi-free. Also specified is a hard cut-off in available struck nucleon energies as dictated by the exclusion principle.

The neutrino and anti-neutrino interaction types relevant to the analysis presented here are charged-current quasi-elastic (Section III A) and pion production (Section III B). The neutrino-induced absolute cross sections for both processes have been measured at MiniBooNE using a flux prediction well determined by HARP data. These cross-section measurements are utilized in the anti-neutrino-mode simulation.

A. Charged current quasi-elastic scattering

To model CCQE interactions, this analysis uses measured cross sections from the MiniBooNE neutrino mode CCQE data [9] and a model which has been found to well-reproduce the kinematics of such events. Specifically, MiniBooNE adopts the CCQE scattering formalism of

Smith-Moniz [25]. The vector component of the interaction is measured by electron scattering experiments and is assumed to have a non-dipole form [26]. The axial-vector form factor employs a dipole construction, containing an “axial mass”, M_A , taken either from MiniBooNE or external data, depending on the neutrino target.

The MiniBooNE mineral oil is composed of C_nH_{2n+2} , $n \sim 20$, and the prediction for CCQE scattering is different for the two flavors of target. In the present analysis, $M_A^{\text{eff}} = 1.35 \pm 0.17$ GeV together with a Pauli blocking adjustment, $\kappa = 1.007 \pm 0.012$ are assumed for bound nucleon scattering. These values come from a high statistics analysis of MiniBooNE ν_μ CCQE events on carbon [9] and are consistent with values recently determined from an independent MiniBooNE neutral-current elastic scattering sample [10]. A previous shape-only study has shown that these CCQE model parameters reproduce the MiniBooNE anti-neutrino-mode data shape [27], and therefore the same M_A^{eff} and κ values are applied to both ν_μ and $\bar{\nu}_\mu$ CCQE scattering events on carbon.

For free scattering off hydrogen, a process accessible to anti-neutrino and not neutrino CCQE events, a value of $M_A = 1.03 \pm 0.02$ GeV is used based on a global fit to previous light target data [28].

In the case of carbon scattering, the superscript “eff”, short for “effective”, on M_A is introduced to allow for the possibility that nuclear effects are responsible for the apparent discrepancy between the MiniBooNE carbon-based measurements and light target results. This is also theoretically motivated by a possible reconciliation between the measurements through a mechanism resulting in intranuclear correlations of greater importance than previously thought [29, 30]. Such a mechanism would indicate a larger CCQE cross section for nuclear targets than for free scattering, which in this case, is reflected in the higher M_A choice for carbon versus hydrogen scattering.

With this model and parameter choice, the MiniBooNE neutrino mode CCQE event rate is found to be 8% higher than prediction, while the total normalization uncertainty is $\sim 10\%$ [9]. In order to more accurately replicate the measured MiniBooNE CCQE cross section, this 8% normalization increase is therefore applied to simulated numu and numubar CCQE events in the anti-neutrino-mode sample.

B. Pion production

Baryonic resonances are the dominant source of single pion production at MiniBooNE. The formalism to describe these events is taken from the Rein-Sehgal model [31], where the relativistic harmonic oscillator quark model is assumed [32]. Eighteen resonances are considered, however the $\Delta(1232)$ is dominant in the energy range spanned by MiniBooNE. Multi-pion production mechanisms are also considered, though their con-

tribution is predicted to be small.

The axial masses in the resonance channels are set simultaneously to reproduce inclusive non-MiniBooNE charged-current data [33]. The extracted values are $M_A^{1\pi} = 1.10 \pm 0.27$ GeV (single pion production) and $M_A^{\text{multi-}\pi} = 1.30 \pm 0.52$ GeV (multi-pion production).

In the present analysis the charged-current single π^+ ($\text{CC}1\pi^+$) prediction with these assumptions is adjusted to reproduce the kinematic distributions measured in MiniBooNE neutrino-mode data [9, 12].

C. Final state interactions

For a neutrino or anti-neutrino interaction with a nucleon bound in carbon, NUANCE propagates the outgoing hadrons including nucleons, mesons and baryonic resonances, and simulates their re-interaction as they exit the nucleus. The initial interaction model employs the impulse approximation which assumes an instantaneous exchange with independent nucleons. Subsequent to the initial neutrino or anti-neutrino interaction, particles produced inside the nucleus are propagated step-wise in 0.3 fm increments until they emerge from the ~ 2.5 fm radius sphere. Intermittently, the probability for hadronic re-interaction is calculated using a radially-dependent nucleon density distribution [34] along with external $\pi - N$, $N - N$ cross-section measurements [35]. For Δ re-interactions ($\Delta + N \rightarrow N + N$), an energy-independent probability of 20% (10%) is taken for $\Delta^+ + N$, $\Delta^0 + N$ ($\Delta^{++} + N$, $\Delta^- + N$) based on K2K data [33] and is assigned 100% uncertainty.

As mentioned earlier, out of all hadronic re-interaction processes, pion absorption and charge exchange ($\pi^\pm + X \rightarrow \pi^0 + X'$) are the most relevant in predicting the composition of the $\text{CC}1\pi^+$ (Section IV A) and CCQE (Section V A) samples studied in this analysis. *Intranuclear* fractional uncertainties on pion absorption (charge-exchange) are set to 25% (30%) based on comparisons between external data [23] and NUANCE. The simulation of these two processes in the detector medium is addressed separately in the detector simulation (Section II C).

IV. MEASURING THE NEUTRINO FLUX COMPONENT IN THE $\text{CC}1\pi^+$ SAMPLE

A. The $\text{CC}1\pi^+$ sample

The events in the $\text{CC}1\pi^+$ sample in anti-neutrino mode originate almost exclusively from ν_μ interactions, making it an excellent candidate for measuring the ν_μ content of the anti-neutrino-mode beam. In the few-GeV energy range, the dominant charged-current single pion production channels contain a final-state π^+ (π^-) in the case of ν_μ ($\bar{\nu}_\mu$) scattering. MiniBooNE cleanly identifies $\text{CC}1\pi^+$ events by selecting 3 “subevents”, attributed to the muon

Under the assumption of $\Delta(1232)$ production by a neutrino scattering off a stationary nucleon target in carbon, the neutrino energy is given by:

$$E_\nu^\Delta = \frac{2(M_p - E_B)E_\mu - (E_B^2 - 2M_p E_B + m_\mu^2 + \Delta M'^2)}{2[(M_p - E_B) - E_\mu + p_\mu \cos \theta_\mu]} \quad (2)$$

where $E_B = 34$ MeV is the binding energy, m_μ is the muon mass, $\Delta M'^2 = M_p^2 - M_\Delta^2$, where M_Δ (M_p) is the $\Delta(1232)$ (proton) mass, p_μ is the muon momentum, and θ_μ is the outgoing muon angle relative to the incoming neutrino beam. Effects not accounted for in the reconstruction include non-resonant pion production, contributions from higher mass Δ resonances and scattering off the quasi-free protons in hydrogen instead of carbon. A shape comparison of reconstructed E_ν^Δ in data and simulation is presented in Figure 3.

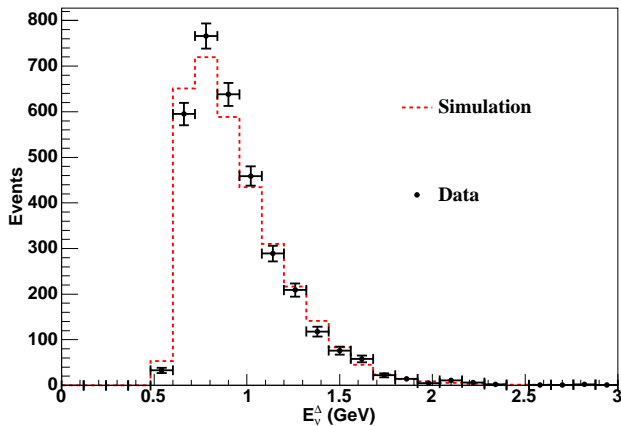


FIG. 3: (Color online) The reconstructed energy spectrum for simulation versus data in the anti-neutrino-mode $\text{CC}1\pi^+$ sample. Simulation is normalized to data, and only statistical errors are shown.

C. Measuring the neutrino flux component in the anti-neutrino-mode $\text{CC}1\pi^+$ sample

The simulation sample is separated into two components: observable $\text{CC}1\pi^+$ events and background. All observable $\text{CC}1\pi^+$ events in the simulation are modeled using the $\text{CC}1\pi^+$ cross section that has been measured in MiniBooNE neutrino-mode data [12]. Given that the majority of the $\text{CC}1\pi^+$ sample in anti-neutrino mode is induced by neutrinos, with this cross-section measurement applied any remaining normalization difference between data and simulation is interpreted as a neutrino flux measurement. Results are presented in Table III.

TABLE III: Anti-neutrino-mode $\text{CC}1\pi^+$ sample details and ν_μ flux component measurement. The measured cross section has been applied to simulation, and the ν_μ flux scale is found by calculating (observed events - expected $\bar{\nu}_\mu$ events) / expected ν_μ events. The reported error is discussed in more detail in Section IV D. The Monte Carlo sample is generated so that the associated statistical error is negligible compared to the other sources of uncertainty.

E_ν^Δ Range (MeV)	Mean Gen. E_ν (MeV)	Events in Data	Expected ν_μ	Expected $\bar{\nu}_\mu$	ν_μ Flux Scale
600 - 700	961	465	556	104	0.65 ± 0.10
700 - 800	1072	643	666	118	0.79 ± 0.10
800 - 900	1181	573	586	97	0.81 ± 0.10
900 - 1000	1285	495	474	78	0.88 ± 0.11
1000 - 1200	1426	571	646	92	0.74 ± 0.10
1200 - 2400	1685	521	614	74	0.73 ± 0.15
Inclusive	1266	3268	3542	563	0.76 ± 0.11

Events in the anti-neutrino mode $\text{CC}1\pi^+$ sample indicate the neutrino flux in anti-neutrino mode is lower than the simulation predicts. The extracted calibration is 0.76 ± 0.11 of the nominal prediction over all reconstructed energies, while the analysis applied to individual energy ranges does not indicate any significant energy dependence.

D. Systematic errors

The systematic error on the neutrino flux measurement using the anti-neutrino-mode $\text{CC}1\pi^+$ sample comes from two sources that are treated as uncorrelated with each other: the uncertainty on the $\text{CC}1\pi^+$ cross section obtained from [12] and the uncertainty in the background prediction. The largest contribution to the uncertainty on the $\text{CC}1\pi^+$ cross section comes from the neutrino-mode flux uncertainty, which is the only systematic error associated with the cross-section measurement that is also independent of the measurement made here. Because the other $\text{CC}1\pi^+$ uncertainties are treated as uncorrelated, a partial cancellation of errors is ignored in the present neutrino flux measurement. This results in a slight overestimate of the neutrino flux uncertainty. Both ν_μ and $\bar{\nu}_\mu$ background events in the sample are assigned 30% uncertainties to conservatively recognize the model dependence of the sample composition. The fractional uncertainty contributions to the flux measurement are presented in Table IV.

TABLE IV: Fractional uncertainty (%) contributions to the neutrino flux measurement in the CC1 π^+ sample. The ν_μ uncertainty is dominated by the CC1 π^+ cross-section error.

E_ν^{QE} Range (MeV)	Statistical	$\bar{\nu}_\mu$	ν_μ	Total Fractional Error
600 - 700	6	9	11	15
700 - 800	5	7	10	13
800 - 900	5	6	10	13
900 - 1000	5	6	10	13
1000 - 1200	5	6	11	13
1200 - 2400	5	5	19	20
Inclusive	2	6	13	14

V. MEASURING THE NEUTRINO FLUX THROUGH MUON ANGULAR DISTRIBUTIONS IN THE CCQE SAMPLE

A. The CCQE sample

The CCQE interaction is the dominant channel in MiniBooNE's energy range. CCQE events typically have two subevents, attributed to the primary muon and the associated decay positron:

$$\begin{aligned} 1: & \bar{\nu}_\mu + p \rightarrow \mu^+ + n \\ 2: & \quad \quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu. \end{aligned} \quad (3)$$

The CCQE sample is therefore similar in formation to the CC1 π^+ sample with one major divergence: a requirement of two subevents instead of three. As shown in Table V, the CCQE selection cuts closely follow those motivated in Section IV A, with a few exceptions appropriate to the inclusion of a single Michel electron. The Michel tank hit and veto PMT hit cuts apply to the second subevent only now (Cuts 5 and 6, respectively), and the muon endpoint-electron vertex cut in Cut 7 is tightened to 100 cm in light of larger backgrounds. The selection cuts outlined here are identical to those employed in a previous shape-only extraction of CCQE model parameters [6] and closely follow those used in the absolute measurement of the ν_μ induced CCQE cross section [9], with only minor differences that result in approximately the same sample efficiency and purity.

Despite the selection cuts, there are formidable backgrounds to the anti-neutrino-mode CCQE sample. Prior to this analysis, simulation estimates the anti-neutrino-mode CCQE sample has a purity just above 50% as shown in Table VI. The major backgrounds include CC1 π^+ and CC1 π^- events, which account for a total of $\sim 20\%$ of the sample, and the ν_μ processes, predicted to be responsible for $\sim 30\%$ of the sample. The 30% predicted ν_μ contamination is investigated and ultimately constrained in this analysis.

A few additional modifications to the simulation are made to accommodate the backgrounds. The largest non-CCQE background in the sample is single pion production which enters the sample due to nuclear effects,

TABLE V: Summary of selection cuts with efficiencies in the CCQE sample. “Purity” refers to $\bar{\nu}_\mu$ CCQE only, and purity and efficiency numbers are sequential.

Cut #	Description	Efficiency (%)	Purity (%)
0	No cuts	100	32
1	Two subevents	49	41
2	1st subevent in event time window $4000 < T(\text{ns}) < 7000$	47	42
3	1st subevent: reconstructed vertex < 500 cm from tank center	38	43
4	1st subevent: tank hits > 200	35	45
5	2nd subevent: tank hits < 200	33	45
6	Both subevents: veto hits < 6	29	49
7	Distance between reconstructed end of 1st subevent and 2nd subevent vertex < 100 cm	25	54

TABLE VI: Predicted composition of the anti-neutrino-mode CCQE sample.

Channel	Contribution (%)
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	54
$\nu_\mu n \rightarrow \mu^- p$	20
$\bar{\nu}_\mu N \rightarrow \mu^+ \pi^- N$ (resonant)	8
$\nu_\mu N \rightarrow \mu^- \pi^+ N$ (resonant)	6
$\bar{\nu}_\mu A \rightarrow \mu^+ \pi^- A$ (coherent)	4
$\bar{\nu}_\mu N \rightarrow \mu^+ \Lambda, \Sigma$	3
$\bar{\nu}_\mu p \rightarrow \mu^+ \pi^0 n$	2
Other	3
All $\bar{\nu}_\mu$	71
All ν_μ	29

including μ^- , π^- capture and final-state interactions; however, in the case of anti-neutrino induced CC1 π^- scattering, due to π^- nuclear capture almost 100% of CC1 π^- events have only two subevents and are experimentally indistinguishable from CCQE. This implies a direct background measurement of CC1 π^- events (analogous to what was done in Ref. [9]) is impossible. Therefore, though the CC1 π^+ yield constraint made in Ref. [9] is strictly appropriate to neutrino induced CC1 π^+ events only, it is applied to both predicted CC1 π^+ and CC1 π^- background events in the CCQE sample.

Many backgrounds to the CCQE sample peak in the most forward scattering region of the muon angular distribution with respect to the incoming neutrino beam. This includes pion production and hydrogen CCQE scattering - while the latter is technically not a background, the proper handling of the difference in nuclear effects between bound and free targets is not straightforward. Additionally, the forward scattering region is strongly correlated with low- Q^2 events, a problematic region both experimentally and theoretically [38]. Such low Q^2 data are dominated by $\bar{\nu}_\mu$ interactions, while the present analysis

is principally interested in backwards scattering muons which is dominated by ν_μ . For these reasons, events with $\cos \theta_\mu > 0.91$ are not included in the fit to data, where θ_μ is the outgoing muon angle relative to the incoming neutrino beam.

B. CCQE event reconstruction

Event reconstruction in the anti-neutrino-mode CCQE sample proceeds similar as in the $\text{CC}1\pi^+$ sample, described in Section IV B. As in the $\text{CC}1\pi^+$ reconstruction, measurement of muon kinematics from the primary interaction is solely responsible for recreating the incident neutrino energy. No requirement is made on the ejected nucleon; this is an important distinction from the CCQE definitions used by other experiments [39, 40], where a single proton track may be required in the case of neutrino-induced CCQE. A similar energy reconstruction as described in Section IV B is implemented, but in this sample a $\bar{\nu}_\mu$ probe is assumed:

$$E_\nu^{\text{QE}} = \frac{2(M_p - E_B)E_\mu - (E_B^2 - 2M_p E_B + m_\mu^2 + \Delta M^2)}{2[(M_p - E_B) - E_\mu + p_\mu \cos \theta_\mu]} \quad (4)$$

where the same definitions from Equation 2 apply and $\Delta M^2 = M_p^2 - M_n^2$, where M_n is the neutron mass. Figure 4 presents the reconstructed energy distributions in simulation and data in the CCQE sample. CCQE scattering with free protons in hydrogen are indistinguishable from those on bound protons in carbon, so all events in data and simulation are reconstructed using the carbon scattering assumption implicit in Equation 4.

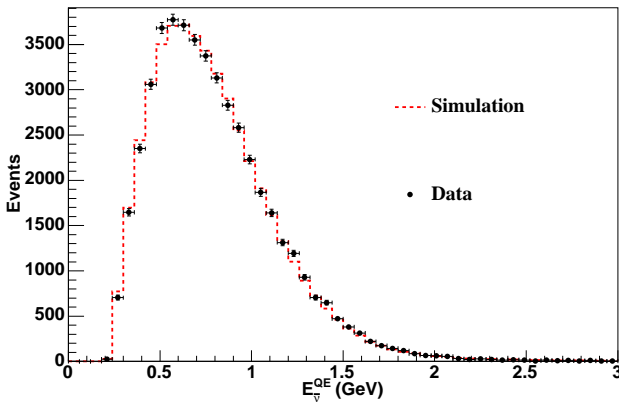


FIG. 4: (Color online) The reconstructed energy spectrum for simulation versus data in the anti-neutrino-mode CCQE sample. Simulation is normalized to data, and only statistical errors are shown.

C. Neutrino flux measurement using CCQE

Neutrino and anti-neutrino CCQE cross sections differ exclusively by an axial-vector interference term that amplifies ν scattering while suppressing $\bar{\nu}$ events. A particularly clean way to exploit this cross section difference is to fit the angular distribution of the primary muon. The contribution from $\bar{\nu}_\mu$ is suppressed in the backward scattering region. Figure 5 shows the predicted ν_μ and $\bar{\nu}_\mu$ contributions to the cosine of the outgoing muon angle.

To measure the neutrino content in the anti-neutrino mode beam, the Monte Carlo (MC) sample is separated into two $\cos \theta_\mu$ templates, one arising from all ν_μ interactions and the other from $\bar{\nu}_\mu$, regardless of interaction channel and nuclear target. A linear combination of these two templates is then formed,

$$T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}}) \equiv \alpha_\nu \nu^{MC} + \alpha_{\bar{\nu}} \bar{\nu}^{MC} \quad (5)$$

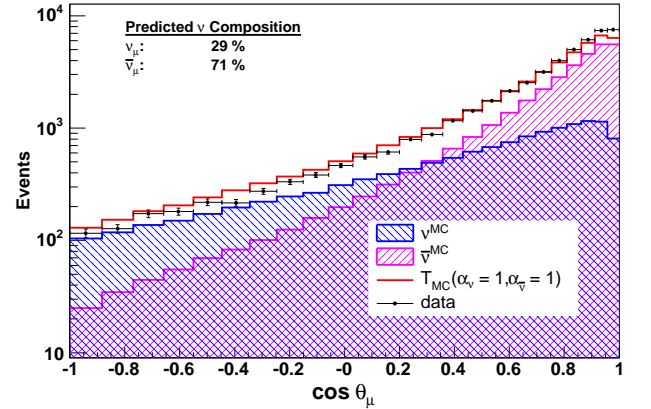


FIG. 5: (Color online) The $\cos \theta_\mu$ distribution of the CCQE sample by neutrino type before fitting. As printed on the figure, 29% of the sample is predicted to be induced by neutrinos. The Monte Carlo sample has been normalized to 5.66×10^{20} protons on target.

where T_{MC} is the total predicted $\cos \theta_\mu$ distribution to be compared to data, α_ν and $\alpha_{\bar{\nu}}$ are neutrino and anti-neutrino rate scales, and ν^{MC} and $\bar{\nu}^{MC}$ are the MC neutrino and anti-neutrino scattering angular predictions, respectively. The modified simulation sample is compared to data by forming a goodness-of-fit χ^2 test as a function of the rate scales:

$$\chi^2 = \sum_{i,j} (T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_i - d_i) M_{ij}^{-1} (T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_j - d_j) \quad (6)$$

where i and j label bins of $\cos \theta_\mu$, d is data and M is the symmetric error matrix given in Equation 7. The error matrix is used to propagate correlated uncertainties on parameters and processes to the quantities reported in the analysis. It is made by first forming weights corresponding to simulation excursions set by Gaussian variations of parameters within their associated error. The difference of these weighted events from the simulated central value forms the error matrix,

$$M_{ij} = \frac{1}{K} \sum_{s=1}^K (N_i^s - N_i^{CV}) \times (N_j^s - N_j^{CV}). \quad (7)$$

Here K simulation excursions are used ($K = 100$ in this analysis), N^s is the re-weighted number of entries corresponding to the s^{th} simulation set and N^{CV} represents the MiniBooNE simulation central value. This technique is further described in Ref. [41]. Bin-by-bin $\cos \theta_\mu$ correlations between ν_μ and $\bar{\nu}_\mu$ are also treated. The specific systematic errors are discussed in the next section.

The fit is performed analytically in three bins of reconstructed energy and also in an inclusive energy sample. Results including statistical and systematic uncertainties are presented in Table VII. The fits to data are shown in Appendix A, where Figure 7 contains both the fitted distributions and the fractional differences between the simulation and data before and after the fits. The adjusted contributions of ν_μ and $\bar{\nu}_\mu$ to the CCQE sample are compared to the prediction in Table VIII.

The χ^2 value for the angular fit in the reconstructed energy range $E_\nu^{QE} > 900$ MeV is unusually low at $\chi^2 = 7$ for 21 degrees of freedom. This is believed due simply to chance, as the statistical error only fit agrees with the data exceptionally well within the error, returning $\chi^2 = 13$ for 21 degrees of freedom.

As the ν_μ angular template has been corrected for the observed cross section per Ref. [9], α_ν may be interpreted as a flux scale factor, and significant deviations from unity would imply a flux mismodeling. Consistent with the independent results reported in Section IV C, fits in the anti-neutrino-mode CCQE sample indicate the true neutrino flux to be somewhat lower than the simulation predicts. Over all reconstructed energies, the neutrino flux component of the anti-neutrino-mode beam should be scaled by 0.65 to match the observed data. Fits in individual reconstructed energy bins show that the neutrino flux component shape is well-modeled. Finding the calibration on the neutrino flux component inconsistent with unity is not surprising, as the neutrino parent pions originate primarily in a poorly constrained production region (cf. Figure 1). The rate scale $\alpha_{\bar{\nu}}$ is ambiguous in interpretation, as the cross section is yet unmeasured.

Care must be taken when comparing these results to the μ^+/μ^- yield numbers reported in the MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation analysis [4, 5], since the interaction prediction is different. In the oscillation analysis the cross section parameters measured in Ref. [6] are employed, which includes $M_A^{\text{eff}} = 1.23(1.13)$ GeV for bound (free)

nucleon CCQE scattering and $\kappa = 1.022$. When the muon angular fit technique described in this section is repeated with this prediction, yield rates of $\alpha_\nu = 0.99 \pm 0.23$ and $\alpha_{\bar{\nu}} = 1.20 \pm 0.23$ are found, as reported in Ref. [5]. With this alternate CCQE scattering model, the angular fit over all reconstructed energies reports a neutrino contamination in the sample of $23 \pm 6\%$, consistent with the $21 \pm 8\%$ contamination found with the scattering assumptions described in Section III A.

The results from this technique depend on knowing the angular distributions of neutrino and anti-neutrino CCQE interactions in the detector. While the procedure relies on exploiting the effect of the interference term in the CCQE cross section, the angular distributions may be somewhat altered by nuclear effects. In this analysis the measured angular distribution of neutrino interactions on carbon [9] is employed, but the measurement relies on the scattering model described in Section III A to predict anti-neutrino interactions. This model does not include two body current effects which may be larger than previously expected [29] and may introduce additional neutrino and anti-neutrino angular differences. Despite this inherent model dependence, the results present a demonstration of a technique aimed at informing future experiments looking to separately constrain neutrino and anti-neutrino events in an unmagnetized environment. By that time, the effect of additional nuclear processes on the angular dependence of anti-neutrino CCQE scattering should be better known.

D. Systematic errors

As the present analysis directly measures the neutrino component in the anti-neutrino-mode beam, systematic errors relating to beam geometry and meson production at the target are not considered. The remaining systematic errors include those arising from detector modeling, the single pion production background, and the cross section parameters in the underlying model. Contributions propagated from these errors to the uncertainty on the parameter α_ν in the inclusive energy sample are given in Table IX.

Apart from final-state interaction uncertainties leading to errors on the cross section, the error on the $\text{CC}1\pi^+$ background contributes to the systematic error through the error labeled “ $\text{CC}1\pi^+$ Constraint” in Table IX. This measurement uncertainty is based on a Q^2 -dependent shape-only scale factor to improve data-simulation agreement in the neutrino-mode $\text{CC}1\pi^+$ sample [3]. The cross section (both CCQE and $\text{CC}1\pi^+$) uncertainty is dominant in these fits and warrants further discussion. Table X offers a breakdown of cross section parameters and associated errors. The error on carbon M_A^{eff} has been reduced from that reported in Ref. [9] to avoid double-counting MiniBooNE systematic errors applicable to both the measurement of M_A^{eff} and the measurement reported here. The 26% uncertainty due to cross-

TABLE VII: Fit results in three energy bins and an inclusive sample. The results are consistent with an over-prediction of the ν_μ contamination of the MiniBooNE anti-neutrino-mode CCQE sample.

E_ν^{QE} Range (MeV)	Mean Generated E_ν (MeV)	Events in Data	α_ν fit	$\alpha_{\bar{\nu}}$ fit	$\rho_{\alpha_\nu - \alpha_{\bar{\nu}}}$ fit correlation	χ^2 (DOF = 21)
< 600	675	15242	0.65 ± 0.22	0.98 ± 0.18	0.33	13
600 - 900	897	16598	0.61 ± 0.20	1.05 ± 0.19	0.49	21
> 900	1277	15626	0.64 ± 0.20	1.18 ± 0.21	0.45	7
Inclusive	950	47466	0.65 ± 0.23	1.00 ± 0.22	0.25	16

TABLE VIII: Fractional composition of the anti-neutrino-mode CCQE sample before and after angular fits.

E_ν^{QE} Range (MeV)	Before Fit (%)		After Fit (%)	
	ν_μ	$\bar{\nu}_\mu$	ν_μ	$\bar{\nu}_\mu$
< 600	25	75	18 ± 6	82 ± 16
600 - 900	26	74	17 ± 6	83 ± 15
> 900	35	65	23 ± 7	77 ± 15
Inclusive	29	71	21 ± 8	79 ± 18

TABLE IX: Summary of systematic error contribution to the scale parameter α_ν in the inclusive energy fit. Individual error contributions are found for the i th systematic error by first repeating the fits with only independent systematics considered. The fractional error contributions are then found by $\sqrt{(\Delta\alpha_\nu/\alpha_\nu)_{\text{syst}i+\text{stat}}^2 - (\Delta\alpha_\nu/\alpha_\nu)_{\text{stat}}^2}$, where $\Delta\alpha_\nu$ is the one-sigma error found reported in Table VII. The statistical error is found by considering the second term only. This method does not account for small changes in the α_ν best fit parameter between the fits considering various errors, and so the individual fractional errors do not add in quadrature to produce the total fractional error reported in Table VII and in the final column.

Source of Error	Fractional Uncertainty (%)
Statistical	8
Detector Modeling	11
CC1 π^+ Constraint	4
Cross Section	26
Total Fractional Error	35

section errors reported in Table IX can be expanded as the quadrature sum of 16% from the 10% normalization errors on $\bar{\nu}_\mu$ and CCQE processes, 14% from the error on M_A and κ , and 15% from the remaining.

As the main contributions to the dominant cross section systematic error apply to both ν_μ and $\bar{\nu}_\mu$ scattering, α_ν and $\alpha_{\bar{\nu}}$ are positively correlated as reported in Table VII.

VI. RESULT COMPARISON

Including all reconstructed energies in the CC1 π^+ sample, a neutrino flux component scale of 0.76 ± 0.11 is found, while the CCQE analysis yields 0.65 ± 0.23 . The measurements are compatible and complementary

TABLE X: Summary of cross-section errors used in this analysis. The bottom portion presents fractional uncertainties assigned to processes *in addition* to parameter errors. Errors given on pion absorption and charge exchange are relevant to pion propagation in the detector medium.

Parameter	Value with Error
M_A^{eff} carbon target	1.35 ± 0.07 GeV
M_A^{eff} hydrogen target	1.03 ± 0.02 GeV
κ	1.007 ± 0.005
E_B	34 ± 9 MeV
Δs	0.0 ± 0.1
$M_A^{1\pi}$	1.10 ± 0.28 GeV
$M_A^{\text{multi}-\pi}$	1.30 ± 0.52 GeV
PF	220 ± 30 MeV
Process	Fractional Uncertainty (%)
π^+ Charge Exchange	50
π^+ Absorption	35
CCQE σ Normalization	10
All $\bar{\nu}_\mu$ σ Normalization	10
$\Delta + N \rightarrow N + N$	100

as each analysis includes energy regions not covered by the other as shown in Fig. 6. The results indicate the simulated neutrino component of the anti-neutrino-mode flux is overestimated by $\sim 30\%$. These flux measurements constrain the very forward π^+ created at the target, where an external data constraint is not available. Results from both methods are summarized in Figure 6, where measurements are placed at the mean of the generated energy distribution for each reconstructed energy sample.

VII. IMPLICATIONS FOR OTHER EXPERIMENTS

The techniques applied here could also aid future neutrino experiments that will test for CP violation in the lepton sector using large unmagnetized detectors. This includes experiments such as NO ν A [42], T2K [43], LBNE [44], LAGUNA [45], and Hyper-K [46]. Additional techniques could offer potentially helpful constraints on

VIII. CONCLUSIONS

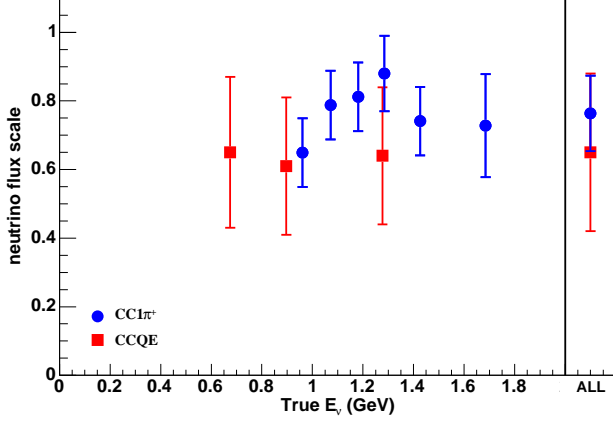


FIG. 6: (Color online) Summary of the neutrino flux constraint in the anti-neutrino-mode beam from the CC1 π^+ (Section IV) and CCQE (Section V) measurements.

the neutrino component in an anti-neutrino-mode beam. This includes taking advantage of the effective lifetime difference between μ^-/μ^+ due to μ^- capture in a nuclear environment. Fitting the lifetime distributions or measuring how often a decay electron is produced could supply constraints that are especially useful as they are independent of the underlying neutrino interaction cross sections. Also, selection of CCQE interactions with and without a proton in the final state may afford additional neutrino versus anti-neutrino tagging capabilities [47, 48].

Two analyses are presented, offering independent measurements of the neutrino flux in the MiniBooNE anti-neutrino-mode beam. Using two event samples dominated by independent physics processes, compatible and complementary results are found. The results from both analyses indicate the prediction of the neutrino flux component of the anti-neutrino beam is over-estimated - the CC1 π^+ analysis (Section IV) indicate the predicted ν_μ flux should be scaled by 0.76 ± 0.11 , while the CCQE angular fits (Section V) yield 0.65 ± 0.23 . Results from repeating the analyses in bins of reconstructed neutrino and anti-neutrino energy indicate that the predicted flux spectrum shape is well modeled. The results from fitting the muon angular distributions in the CCQE sample has already been employed in the MiniBooNE oscillation analysis [4, 5], while the CC1 π^+ -based measurement will likely be more valuable to MiniBooNE anti-neutrino cross section extractions, as it is both model independent and carries comparatively smaller uncertainty. These types of analyses, along with others discussed in Section VII may be of use to present and future precision neutrino experiments testing CP violation with neutrino and anti-neutrino beams.

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Appendix A: CCQE angular fit details

This appendix presents details on the CCQE angular fit results described in Section V. The fits to data are

plotted in Figure 7 along with the fractional differences between data and MC before and after fitting.

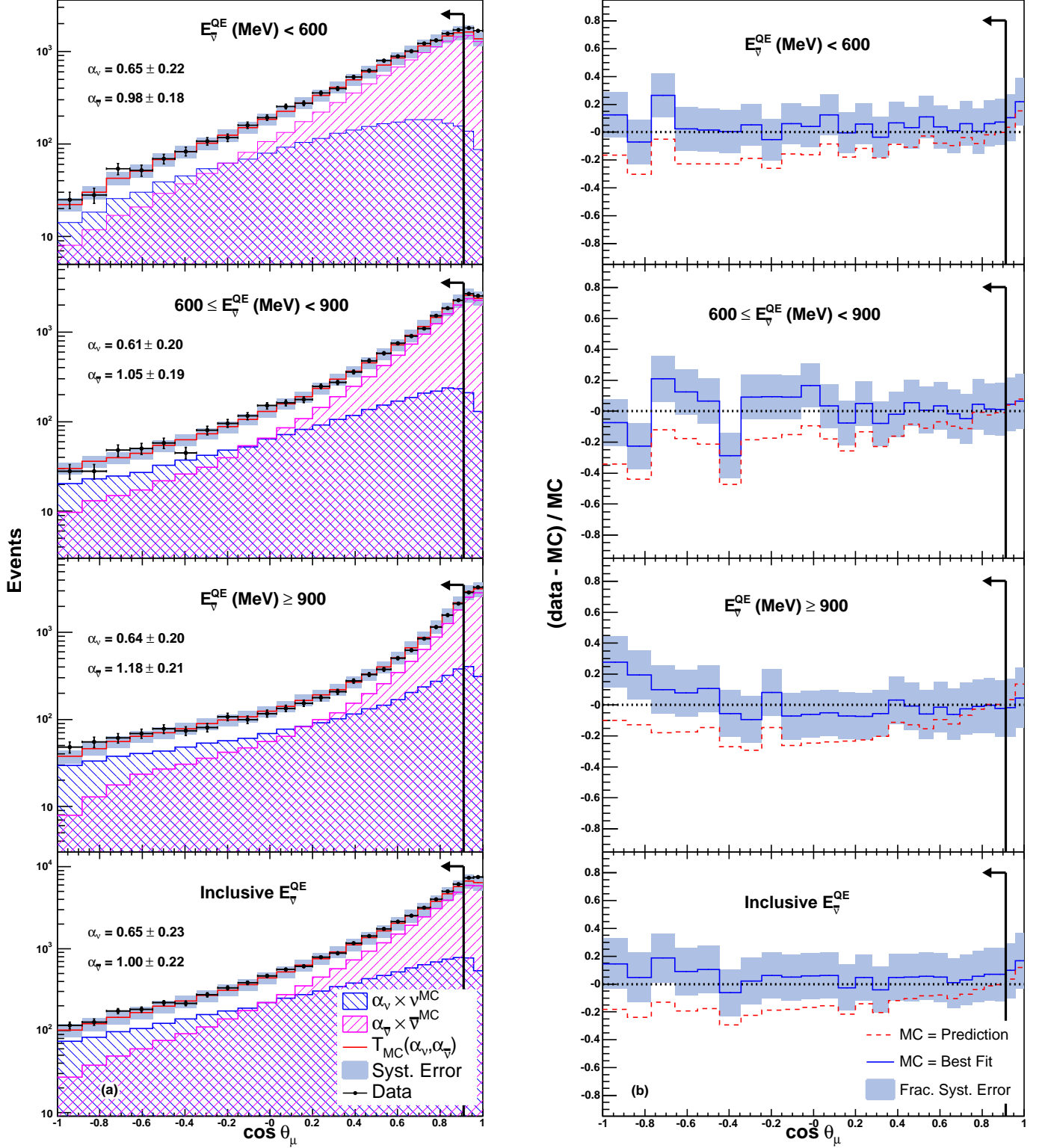


FIG. 7: (Color online) Results of the muon angular fits to the CCQE data described in Section V. Shown are (a) the fits and (b) fractional differences $(\text{data} - \text{simulation}) / \text{simulation}$ for both the unmodified prediction and the best fit. Along with an inclusive sample, three reconstructed energy bins are considered. The before-fit simulation is absolutely normalized to 5.66×10^{20} protons on target. Only events with $\cos \theta_\mu < 0.91$ participate in the fit.