Search for an anomalous excess of charged-current $\nu$ interactions without pions in the final state with the MicroBooNE experiment

P. Abratenko,33 R. An,14 J. Anthony,4 L. Arellano,18 J. Asaadi,32 A. Ashkenazi,30 S. Balasubramanian,11 B. Baller,11 C. Barnes,20 G. Barr,25 V. Basque,18 L. Bathe-Peters,15 O. Benevides Rodrigues,29 S. Berkman,11 A. Bhandari,18 A. Bhat,29 M. Bishai,2 A. Blake,16 T. Bolton,15 J. Y. Book,13 L. Camilleri,9 D. Caratelli,11 I. Caro Terrazas,8 F. Cavanna,11 G. Cerati,11 Y. Chen,1 D. Cianci,9 J. M. Conrad,19 M. Convery,26 L. Cooper-Treanor,36 J. I. Crespo-Anadón,5 M. Del Tutto,11 S. R. Dennis,2 P. Detje,4 A. Devitt,16 R. Diurba,21 R. Dorrill,14 K. Duffy,11 S. Dytman,24 B. Eberly,28 A. Ereditato,1 L. Escudero Sanchez,3 2 J. J. Evans,18 R. Fine,17 G. A. Fiorentini Aguirre,27 R. S. Fitzpatrick,20 B. T. Fleming,36 N. Foppiani,13 D. Franco,36 A. P. Furmanski,21 D. Garcia-Gamez,12 S. Gardiner,11 G. Ge,9 S. Gollapinni,31,17 O. Goodwin,18 E. Gramellini,11 P. Green,18 H. Greenlee,11 W. Gu,2 R. Guenette,13 P. Guzowski,18 L. Hagaman,36 O. Hen,19 C. Hilgenberg,21 G. A. Horton-Smith,15 A. Hourlier,19 R. Itay,26 C. James,11 X. Ji,2 L. Jiang,34 J. H. Jo,36 R. A. Johnson,7 Y.-J. Jwa,9 D. Kalra,9 N. Kamp,19 N. Kaneshige,3 G. Karagiorgi,9 W. Ketchum,11 M. Kirby,11 T. Kobilarcik,11 I. Kreslo,1 R. LaZur,8 I. Lepetic,25 K. Li,36 Y. Li,2 K. Lin,17 A. Lister,16 B. R. Littlejohn,14 W. C. Louis,17 X. Luo,5 K. Manivannan,29 C. Mariani,34 D. Marsden,18 J. Marshall,35 D. A. Martinez Caicedo,27 K. Mason,33 A. Mastbaum,25 N. McConkey,18 V. Meddage,15 T. Mettler,1 K. Miller,6 J. Mills,33 K. Mistry,18 A. Mogan,31 T. Mohayal,11 J. Moon,19 M. Mooney,8 A. F. Moor,4 C. D. Moore,11 L. Mora Lepin,18 J. Mousseau,20 M. Murphy,34 D. Naples,24 A. Navrer-Agasson,18 M. Nebot-Guino,10 R. K. Neely,15 D. A. Newmark,17 J. Nowak,16 M. Nunes,29 O. Palamara,11 V. Paolone,24 A. Papadopoulou,19 V. Papavassiliou,22 S. F. Pate,22 N. Patel,16 A. Paudel,15 Z. Pavlovic,11 E. Piasetzky,30 J. Prince,13 X. Qian,2 J. L. Raaf,11 V. Radeka,2 A. Rafique,15 M. Reggiani-Guzzo,18 L. Ren,22 L. C. J. Rice,24 L. Rochester,26 J. Rodriguez Rondon,27 M. Rosenberg,24 M. Ross-Lonergan,9 G. Scanavini,36 D. W. Schmitz,4 A. Schukraft,11 W. Seligman,9 M. H. Shaevitz,9 R. Sharrank,33 J. Shi,4 J. Sinclair,1 A. Smith,4 E. L. Snider,11 M. Soderberg,29 S. Soldner-Rembold,18 S. R. Soleti,23,13 P. Spentzouris,11 J. Spitz,20 M. Stancari,11 J. St. John,11 T. Strauss,11 K. Sutton,9 S. Sword-Fehlberg,22 A. M. Szulc,10 W. Tang,31 K. Terao,26 M. Thomson,4 C. Thorpe,16 D. Totani,3 M. Toups,11 Y.-T. Tsai,26 M. A. Uchida,4 T. Usher,26 W. Van De Pontseele,23,13 B. Viren,2 M. Weber,1 H. Wei,2 Z. Williams,32 S. Wolbers,11 T. Wongjirad,33 M. Wospakrik,11 K. Wresilo,4 N. Wright,19 W. Wu,11 E. Yandel,3 T. Yang,11 G. Yarbrough,31 L. E. Yates,19 H. W. Yu,2 G. P. Zeller,11 J. Zennamo,11 and C. Zhang2 (The MicroBooNE Collaboration)*

1 Universitàt Bern, Bern CH-3012, Switzerland
2 Brookhaven National Laboratory (BNL), Upton, NY, 11973, USA
3 University of California, Santa Barbara, CA, 93106, USA
4 University of Cambridge, Cambridge CB3 0HE, United Kingdom
5 Centro de Investigaciones Energéticas, Medioambientales y Tecno-
6 los (CIEMAT), Madrid E-28040, Spain
7 University of Chicago, Chicago, IL, 60637, USA
8 University of Cincinnati, Cincinnati, OH, 45221, USA
9 Colorado State University, Fort Collins, CO, 80523, USA
10 Columbia University, New York, NY, 10027, USA
11 University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
12 Universidad de Granada, Granada E-18071, Spain
13 Harvard University, Cambridge, MA 02138, USA
14 Illinois Institute of Technology (IIT), Chicago, IL 60616, USA
15 Kansas State University (KSU), Manhattan, KS, 66506, USA
16 Lancaster University, Lancaster LA1 4YW, United Kingdom
17 Los Alamos National Laboratory (LANL), Los Alamos, NM, 87545, USA
18 The University of Manchester, Manchester M13 9PL, United Kingdom
19 Massachusetts Institute of Technology (MIT), Cambridge, MA, 02139, USA
20 University of Michigan, Ann Arbor, MI, 48109, USA
21 University of Minnesota, Minneapolis, MN, 55455, USA
22 New Mexico State University (NMSU), Las Cruces, NM, 88003, USA
23 University of Oxford, Oxford OX1 3RH, United Kingdom
24 University of Pittsburgh, Pittsburgh, PA, 15260, USA
25 Rutgers University, Piscataway, NJ, 08854, USA
26 SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA
27 South Dakota School of Mines and Technology (SDSMT), Rapid City, SD, 57701, USA
28 University of Southern Maine, Portland, ME, 04104, USA
29 University of Southern Maine, Portland, ME, 04104, USA
30 University of Southern Maine, Portland, ME, 04104, USA
31 University of Southern Maine, Portland, ME, 04104, USA
32 University of Southern Maine, Portland, ME, 04104, USA
33 University of Southern Maine, Portland, ME, 04104, USA
34 University of Southern Maine, Portland, ME, 04104, USA
This article presents a measurement of $\nu_e$ interactions without pions in the final state using the MicroBooNE experiment and an investigation into the excess of low-energy electromagnetic events observed by the MiniBooNE collaboration. The measurement is performed in exclusive channels with $1\nu_e Np\pi^0$ and without $1\nu_e 0p\pi^0$ visible final-state protons using $6.86 \times 10^{20}$ protons on target of data collected from the Booster Neutrino Beam at Fermilab. Events are reconstructed with the Pandora pattern recognition toolkit and selected using additional topological information from the MicroBooNE liquid argon time projection chamber. Using a goodness-of-fit test the data are found to be consistent with the predicted number of events with nominal flux and interaction models with a $p$-value of 0.098 in the two channels combined. A model based on the low-energy excess observed in MiniBooNE is introduced to quantify the strength of a possible $\nu_e$ excess. The analysis suggests that, if an excess is present, it is not consistent with a scaling of the $\nu_e$ contribution to the flux as predicted by the signal model used in the analysis. Combined, the $1\nu_e Np\pi^0$ and $1\nu_e 0p\pi^0$ channels do not give a conclusive indication about the tested model, but separately they both disfavor the low-energy excess model at >90% CL. The observation in the most sensitive $1\nu_e Np\pi^0$ channel is below the prediction and consistent with no excess. In the less sensitive $1\nu_e 0p\pi^0$ channel the observation at low energy is above the prediction, while overall there is agreement over the full energy spectrum.

I. INTRODUCTION

Neutrino physics has entered an era of precision measurements of the parameters that describe three-flavor oscillations [1]. At the same time, a broad set of experimental results, collectively referred to as short-baseline anomalies [2–6], is in tension with the three-neutrino paradigm and remains without resolution. These short-baseline anomalies have often been linked to the physics signature of $\mathcal{O}(\text{eV})$ sterile neutrinos [7]. Recent long-baseline sterile-neutrino oscillation searches [8, 9], however, show tension with this interpretation, and other explanations for these anomalies may need to be considered. The observation of an excess of low-energy electromagnetic activity by the MiniBooNE experiment [5] is one example of these anomalies. Many scenarios have been suggested to explain the origin of the MiniBooNE excess of low-energy electromagnetic showers, including new physics such as sterile neutrino oscillations and decay [10, 11], dark-sector portals [12–14], heavy neutral leptons [15, 16], non-standard Higgs models [17–19], or Standard Model processes such as an enhancement of photon backgrounds [20].

The MicroBooNE experiment [21] was built to explore the nature of the low-energy excess of events observed by MiniBooNE. Operating in the same Fermilab Booster Neutrino Beamline (BNB), it is in a position to examine the nature of low-energy electromagnetic activity with the capabilities of the liquid argon time projection chamber (LArTPC) detector technology. A set of analyses, including the one presented here, have been designed to measure both electron neutrino interactions in multiple topologies [22–24], as well as single photon events [25]. This article presents a measurement of the rate of charged current (CC) electron neutrino interactions without pions in the final state, and investigates the possibility of low-energy $\nu_e$ interactions as an explanation for the MiniBooNE observation of an anomalous excess.

Electron neutrinos that undergo CC interactions will produce a visible electron in the detector, which develops into an electromagnetic (EM) shower, along with possible hadronic activity such as protons and pions. This analysis performs a measurement of $\nu_e$ interactions with any number of protons and without visible pions in the final state ($1\nu_e Xp0\pi^0$, $X \geq 0$). This is designed to match MiniBooNE’s single electron-like Cherenkov ring signal topology [26]. The presence of visible protons ($1\nu_e Np\pi^0$, $N \geq 1$) provides additional handles for background rejection. Furthermore, the final state with no protons ($1\nu_e 0p\pi^0$) may be sensitive to a broad range of models [12–15, 18, 27] that predict single-shower events and go beyond the electron neutrino interpretation of the MiniBooNE anomaly. Together these motivate the choice to develop separate, orthogonal selections for events with and without protons in the final state. We focus on the use of calorimetric and topological information provided by the LArTPC technology to perform particle identification (PID) and measure electron neutrino interactions in a broad phase space. Example candidate events in these topologies from data are shown in Fig. 1. The neutrino flux and interaction systematic uncertainties associated with the selected electron neutrinos are constrained using a high-statistics inclusive measurement of CC muon

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* microboone_info@fnal.gov
neutrino interactions in the BNB. Analysis results are obtained through a series of statistical tests with the introduction of an empirical model which interprets the MiniBooNE anomaly as an enhancement of the flux of low energy electron neutrinos.

This article is organized as follows. Section II describes the neutrino beamline and MicroBooNE detector. Section III provides details of the tools used to simulate neutrino events. Section IV presents the reconstruction methods used to identify neutrino interactions. Section V presents the PID methods as well as the \( \nu_\mu \) and \( \nu_e \) event selections. Section VI describes the blinding procedure and studies on data sidebands. Section VII details the formalism of the procedure used to reduce uncertainties based on the \( \nu_\mu \) observation, referred to as the \( \nu_\mu \) constraint. Section VIII presents the analysis results.

II. BEAMLINE AND DETECTOR OVERVIEW

This section provides a brief overview of the Booster Neutrino Beamline, the MicroBooNE detector, and the dataset used for the analysis. The MicroBooNE detector sits at a distance of 468.5 m from the BNB target, on-axis with respect to the neutrino beam. The neutrino beam begins with 8 GeV protons extracted from the Fermilab Booster synchrotron. These protons interact with a beryllium target and produce pions and kaons, which then decay to produce neutrinos. The resulting neutrino beam is composed predominantly of muon neutrinos with a small (\(< 1\%\)) electron neutrino component. This electron neutrino component produced by meson decay chains in the BNB is referred to as “intrinsic \( \nu_e \)” in this article. The BNB is structured in spills, each with a duration of 1.6 \( \mu s \) and an intensity of up to \( 5 \times 10^{12} \) protons, with an average repetition rate of up to 5 Hz. Additional details on the BNB are found in Ref. [28, 29].

The MicroBooNE detector [21] consists of a time projection chamber (TPC) and a photon detection system. The TPC measures 2.56 m (drift coordinate, \( x \)) \( \times \) 2.32 m (vertical, \( y \)) \( \times \) 10.36 m (beam direction, \( z \)) and contains 85 tonnes of liquid argon in its active volume. Charged particles traversing the detector ionize the argon leaving trails of ionization electrons which drift under the 273 V/cm electric field towards the anode where three planes of wires record induced currents and collect the ionization electrons. The three planes of wires, spaced 3 mm apart and oriented at 0 degrees (vertical) and at \( \pm 60 \) degrees, produce three different two-dimensional views of the neutrino interaction and allow for three-dimensional reconstruction with \( \mathcal{O}(\text{mm}) \) spatial resolution. The low-noise TPC electronics allow for measurement of the charge with few percent resolution [30]. Combined, these features enable the MicroBooNE detector to record the final-state particles produced by neutrino interactions with the detail required to perform particle identification and accurately measure particle kinematics. The light detection system, composed of 32 photomultiplier tubes (PMTs), has a timing resolution of \( \mathcal{O}(\mu s) \), which allows us to select events in the BNB time window and to remove a large fraction of the cosmic-ray background. In addition, a cosmic-ray tagger (CRT) [31]
Modeling uncertainties on neutrino interactions in GENIE are obtained in three different ways. For model parameters that are estimated using the tune, we use the parameter uncertainty from the fit. For all other parameters in the model we use uncertainties as provided by the GENIE collaboration. Finally, for parameters for which an uncertainty was not provided, we estimate the uncertainty in other ways, such as by choosing the full range between different available models that cover the world data. The treatment of systematic uncertainties in the neutrino interaction model is further detailed in Ref. [42], including an inconsistency in the treatment of the final state interaction uncertainty which has a negligible impact on the analysis. The effect of cross section uncertainties on the predicted neutrino event rate after selection is about 20%, and constitutes the leading source of systematic uncertainty for the analysis.

C. Detector model

MicroBooNE’s detector response is modeled with multiple simulation tools. Geant4 [43] v10.3.03c is used to simulate the propagation of particles through the detector. The propagation of light and charge in the detector is done within LArSoft.

The MicroBooNE TPC readout electronics and wire response are determined using a simulation of the induced charge from drifting electrons [30, 44]. The production of scintillation light is simulated through a voxelized look-up library created from a detailed Geant4 simulation to model photon propagation. Several detector simulation components are implemented using a data-driven approach. These involve effects that lead to a non-uniform detector response in space and time. Electric field distortions due to space-charge buildup in the active volume are accounted for through MicroBooNE’s data-driven electric field maps [45, 46]. Non-uniformities across the detector due to electron lifetime or wire response are simulated in a time-dependent way when appropriate. Ion recombination is simulated using a modified box model [47].

As MicroBooNE is a surface detector, cosmic rays are the largest background to neutrino interactions. A data-driven method is used to eliminate the need to simulate the high rate of cosmic rays passing through the detector as well as intrinsic noise in the TPC and PMT electronics. This starts with a dedicated data stream which is collected in periods when there is no beam and provides a sample of detector activity from both cosmic rays and electronics noise. Then, to form the beam simulation, TPC and PMT waveforms from simulated neutrino interactions are merged with this beam-off data-stream, ensuring faithful modelling of cosmic-ray backgrounds and noise. We use this approach for the simulation of neutrino interactions taking place both inside and outside the TPC fiducial volume; the latter are referred to as “dirt” background events in this analysis and include in-

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teractions in the LAr outside the TPC fiducial and in
the walls of the cryostat as well as the rock around the
detector cavern.

Detector response systematic uncertainties include the
propagation of final-state particles as well as the forma-
tion of light and charge signals. Uncertainties associated
with the TPC dominate over the ones associated with
the light collection system, with a total uncertainty of
10–15% in the $\nu_e$ event rate. Mis-modeling of the wire
response, electric field map, and ion recombination each
contribute at a smaller level but in similar magnitude.
The treatment of wire response systematics are discussed in
[48]. The impact of final state particle propagation is
assessed by varying charged pion and proton reinterac-
tion cross sections available from external data, using the
Geant4Reweight [49] framework. This leads to $O(1\%)$
uncertainties on the event rate. Systematic uncertain-
ties associated with light production impact only the first
stages of the analysis related to cosmic-ray rejection and
lead to uncertainties of 3–5% on the event rate. Uncer-
tainties due to the limited sample size are also included
in the analysis and in terms of $\nu_e$ event rate they vary
from $O(1\%)$ for the most populated bins to $O(100\%)$
for the bins with very small prediction at high energy.

D. Unfolded median MiniBooNE $\nu_e$ excess model

This analysis searches for an excess of electron neu-
trino events over the predicted intrinsic interaction rate.
To benchmark the analysis performance and calculate
sensitivity to potential new physics, we adopt a model
constructed using the MiniBooNE dataset to obtain a
sensitivity to potential new physics, we adopt a model
constructed using the MiniBooNE dataset to obtain a

To construct the model, the background-subtracted ex-
cess of data events from MiniBooNE’s 2018 result [5] is
unfolded using MiniBooNE’s electron neutrino energy re-
construction smearing matrix, constructed with the NU-
ANCE [50] neutrino interaction simulation using a CC
quasi-elastic energy definition, and accounting for Mini-
BooNE’s energy smearing and selection efficiency. This
predicts the rate of electron neutrinos as a function of
true neutrino energy above 200 MeV. The ratio between
the predicted rate from MiniBooNE and that of the in-
trinsic electron neutrino component in MiniBooNE’s sim-
ulation is used to obtain an energy-dependent flux scaling
factor for the excess under the electron neutrino hypoth-
esis. These energy-dependent weights are applied to the
rate of intrinsic electron neutrino events predicted by Mi-
croBooNE’s flux and cross section simulation to obtain
a prediction for the MiniBooNE $\nu_e$-like excess in the Mi-
croBooNE detector. Uncertainties from the MiniBooNE
measurement are not propagated in our signal prediction
as an accurate determination of correlations with Mini-
BooNE uncertainties is beyond the scope of this work
and will require a joint analysis of the two experiments.
We will refer to this model in the article as the eLEE
model. Figure 2 shows the truth-level intrinsic $\nu_e$
spectrum, broken into final state particles, and the additional
contribution of the prediction of eLEE model events. In
this plot, and throughout this work, protons and charged
pions are considered “visible” and counted if their true
kinetic energy is above 40 MeV. A scaling factor $\mu$ is used
to vary the normalization of the excess component of the
flux. Systematic uncertainties on eLEE signal events are
applied analogously to those for intrinsic $\nu_e$ interactions,
consistent with their implementation as an enhancement
of the intrinsic $\nu_e$ flux. Since it is constructed using an
unfolding procedure based on the neutrino energy, this
model is only used to predict the event rate as a function
of reconstructed neutrino energy and not for predictions
in other kinematic variables.

Although it does not fully characterize the MiniBooNE
excess, this empirical model provides a benchmark that
allows the analysis to quantitatively relate to the $\nu_e$
interpretation of the MiniBooNE excess and to provide
a reproducible reference for further interpretations. As
mentioned in Sec. I however, different theoretical mod-
els, such as sterile neutrino oscillations or more exotic
phenomena, can lead to different predictions in Micro-
BooNE. These are not directly explored here and are left
for future work.

IV. NEUTRINO EVENT RECONSTRUCTION

This section describes the methods used to reconstruct
events, separate cosmic-rays from neutrino interactions,
and calculate neutrino energy.

A. Event reconstruction

Event reconstruction in the MicroBooNE TPC starts with the processing of the electronic signal waveforms recorded on wires, which includes noise suppression [51] and signal processing [30, 44]. Gaussian-shaped pulses on the waveforms, called “hits”, are then identified, and the associated wire number, time, and integrated charge are inputs to later reconstruction steps.

This analysis uses the Pandora [52] event-reconstruction. Pandora is a multi-algorithm pattern recognition toolkit that performs particle tracking for LArTPC detectors. It has been extensively developed within the MicroBooNE collaboration and used for numerous published results [34–39, 53–55]. It starts with the two-dimensional hit coordinates from each plane and outputs three-dimensional particles categorized in terms of their hierarchy in the neutrino interaction. In this hierarchy primary particles are directly produced in the neutrino interaction, while those from their decay or interaction with the argon are secondaries. Particles are classified as shower-like (electrons and photons) or track-like (muons, charged pions, and protons) using a score ranging from 0 to 1. The Pandora pattern recognition is further complemented by analysis-specific tools that enhance the PID and track-shower separation capabilities with an emphasis on ensuring powerful muon/proton and electron/photon separation for particles from low energy neutrino interactions (see Sec. V A).

TPC detector calibrations implement position- and time-dependent corrections that provide a uniform detector response in addition to absolute gain calibrations necessary for calorimetric energy measurements and PID. These include a calibration of the position-dependent electric field [45] using MicroBooNE’s UV-laser as well as calibrations of the electron lifetime, wire-response, and absolute charge. MicroBooNE’s overall calibration strategy is described in Ref. [56] and relies on through-going and stopping cosmic muons.

B. Cosmic-ray rejection

The near-surface location and the low neutrino interaction rate in the detector lead to significant cosmic-ray contamination. For each beam spill, O(10) cosmic rays cross the detector in the 2.3 ms TPC drift window. Conversely, approximately one in every 1000 spills lead to a neutrino interaction in the active volume for a ν-tocosmic ratio of 10^{-4}. Scintillation light is used to suppress cosmic-ray backgrounds, first as part of an online trigger selection and subsequently through an offline analysis filter. A requirement to observe prompt scintillation light in coincidence with the beam rejects 98% of recorded beam-spills while accepting more than 99% for ν_e interactions with neutrino energy greater than 200 MeV.

At this stage in the analysis, selected events are still dominated by cosmic-ray interactions which occur in time with the 1.6 µs BNB spill. Through-going or out-of-time TPC interactions are rejected as obvious cosmic rays and removed from further analysis. The three-dimensional charge-pattern of the remaining interactions identified in the TPC is compared to the pattern of scintillation light collected on the detector’s PMTs. Compatibility between the absolute charge and light, as well as their relative position in the TPC, is required. Including these tools in the selection leads to an additional suppression of cosmic-ray interactions by a factor of ten, with an integrated efficiency of 83% for both ν_e and νµ CC interactions.

The CRT [31] provides an additional tool for cosmic rejection. CRT information is available only for data taken after December 2017, when it was integrated in MicroBooNE’s analysis chain. Its usage in this analysis is limited to the νµ selection (Sec. V B).

C. Energy reconstruction

The MicroBooNE LArTPC can detect particles with a threshold of few to tens of MeV and measure the energy deposited in the neutrino interaction with high precision. Energy reconstruction is performed calorimetrically for electromagnetic (EM) showers and based on measurements of particle range for track-like particles. Selections in this analysis require particle containment in the detector (see Sec. V). Range-based track energy measurements deliver very good energy resolution, which is estimated from simulation to be 3% for muons and < 2% (< 9%) for protons with kinetic energy > 100 MeV (> 40 MeV). The EM shower energy is measured by integrating the deposited energy (E_{calorimetric}) and relying on simulation of electron showers to obtain a correction factor which accounts for inefficiencies in collecting the full energy deposited [57]. This leads to a reconstructed energy definition of \( E_{\text{corrected}} = E_{\text{calorimetric}}/0.83 \). The electron energy resolution is ≤ 12% and is dominated by the charge clustering inefficiencies discussed above. The reconstructed neutrino energy for ν_e and νµ interaction candidates is calculated using:

\[
E_{\text{reco}}^{\nu_e} = E_{\text{electron}}^{\text{corrected}} + \sum_{\text{tracks}} E_{\text{range}}^{\text{proton}} \tag{1a}
\]

\[
E_{\text{reco}}^{\nu_\mu} = E_{\text{muon}}^{\text{range}} + \sum_{\text{other tracks}} E_{\text{range}}^{\text{proton}} + 0.105 \text{ GeV} \tag{1b}
\]

where 0.105 GeV is the muon mass. In the energy definition we assume that all tracks other than the selected muon are protons, which matches the ν_e selection without pions, but represents an approximation for the inclusive νµ selection. This definition achieves 15% energy resolution.
resolution for both selected $\nu_e$ and $\nu_\mu$ events in the low energy region primarily targeted by this analysis. For $\nu_e$ events this definition measures the the energy deposited by charged final state particles above threshold and provides an accurate estimate, with an average bias at the percent level; when compared to the true neutrino energy, however, it typically underestimates by 16% (9%) for selected $1\sigma \geq 0\pi$ ($1\sigma \geq 0\pi$) events. More details on PID are described in Sec. V.

V. NEUTRINO EVENT SELECTIONS

Neutrino candidate events are initially identified using the reconstruction methods described in Sec. IV. The following section presents a description of several of the PID tools developed for this analysis as well as the $\nu_\mu$ and $\nu_e$ selections in which they are used.

A. Particle identification

The primary PID tasks required for this analysis are the separation of highly ionizing proton tracks from minimally ionizing muons and pions as well as the separation of photon and electron electromagnetic showers. To distinguish stopping muons from protons we leverage the difference in the energy loss profile at the Bragg peak through a measurement of the energy loss per unit length ($dE/dx$) versus particle residual range. A probability density function for simulated protons and muons is used to construct a likelihood function that combines the measured $dE/dx$ at each point along a particle’s trajectory from the calorimetric information on all three planes [58]. This tool provides a 90% relative efficiency for proton selection with a 5% mis-identification rate. Track PID is used to identify muon candidates produced by $\nu_\mu$ CC interactions, isolate protons, and remove pion candidates.

Two key features are used to achieve electron-photon separation: the calorimetric measurement of $dE/dx$ at the start of the shower and the displacement of the electromagnetic shower’s start position from the primary vertex in neutrino interactions with hadronic activity. To evaluate $dE/dx$, reconstructed showers are fit using a Kalman filter [59] based procedure to identify the main shower trunk and reject hits that are transversely or longitudinally displaced. Values of $dE/dx$ measured in the first few centimeters of the electromagnetic shower, before it starts to cascade, are used to compute a median $dE/dx$ characteristic of the shower’s energy loss [60]. Information from all three wire planes is used to optimize the ability to perform electron-photon separation independently of particle orientation. Multiple ranges at the shower start point are used to evaluate $dE/dx$ to account for the potential impact of protons at the vertex and early branching of the electromagnetic shower and provide additional separation power. The $dE/dx$ variable is shown in Fig. 3. Good separation between electron and photon showers is observed and contributes to the $\pi^0$ background rejection achieved by this analysis. In this and other data/simulation comparison plots shown in the article data points are shown with associated statistical uncertainty, computed as $\sqrt{N}$, while systematic uncertainties on the prediction are shown as a shaded gray band.

B. $\nu_\mu$ measurement

The vast majority of neutrinos reaching the MicroBooNE detector are muon neutrinos. They come from the same flux of parent hadrons and interact on the same target argon in the detector as the electron neutrinos. This makes the measurement of high-statistics $\nu_\mu$ interactions a valuable handle with which to validate and constrain intrinsic $\nu_e$ flux and cross section systematic uncertainties. This is done with a $\nu_\mu$ CC inclusive selection that allows any number of final state hadrons and prioritizes performance at low energy. A muon neutrino candidate is identified by the presence of a muon candidate inside the TPC fiducial volume. The muon is required to be contained, which preserves good efficiency for low-energy $\nu_\mu$ interactions, while suppressing cosmic-ray muon backgrounds. Cosmic rays are the primary background for $\nu_\mu$ CC events, and an additional 64%
of these are removed using the CRT. The $\nu_\mu$ constraint only uses $2.13 \times 10^{20}$ POT of data collected after December 2017, when the CRT was available. Events surviving these selection requirements are required to have a track PID with a muon-like value. Consistency is required between two independent measurements of muon energy: the range-based energy estimation and one based on multiple Coulomb scattering as described in Ref. [61]. The reconstructed neutrino energy distribution for the final $\nu_\mu$ selection is shown in Fig. 4. The data sample contains 13,346 events with a predicted $\nu_\mu$ CC purity of 77%. The main backgrounds are cosmic ray and neutral-current neutrino interactions. Data and simulation are found to agree within systematic uncertainties in reconstructed neutrino energy as well as in other muon neutrino kinematic variables. These include the muon energy and angle with respect to the beam, and were tested quantitatively accounting for all uncertainties and their correlations.

C. $\nu_e$ selections

Electron neutrinos are measured with two separate selections targeting events with and without visible protons. These are referred to as the 1eNp0$\pi$ and 1e0p0$\pi$ selections where $N \geq 1$. In simulation, we define a proton as visible if it has a kinetic energy of at least 40 MeV. Combined, these span the signal definition of electron neutrinos measured by the MiniBooNE experiment: events with a single electron, any number of protons, and no pions.

The analysis targets contained $\nu_e$ interactions occurring in the fiducial volume, defined by a boundary of 10 cm in the drift coordinate, 15 cm in the vertical, and 10 and 50 cm from the front and end of the TPC respectively. The selections rely on a common pre-selection which identifies an event as $\nu_e$-like. An event is defined as $\nu_e$-like if there is a contained reconstructed electromagnetic shower with at least 70 MeV of deposited energy. The reconstructed energy requirement removes Michel electrons from cosmic- or neutrino-induced muons. Events are then further classified depending on the presence or absence of proton candidates.

The 1eNp0$\pi$ and 1e0p0$\pi$ selection definitions split after pre-selection, but the strategy and inputs used for the following steps are the same for both. Events are classified based on topological and calorimetric information such as the track PID score and $dE/dx$ as described earlier. Additional handles are used to separate $\nu_\mu$ events from events with a $\pi^0$. These are the distance between the neutrino interaction vertex and the start point of the shower, known as the conversion distance, and a second shower search. This analysis does not use kinematic quantities in the selection criteria to limit the model dependence of the results. A set of selection requirements called the “loose” selection is defined using these variables to remove large portions of the backgrounds for higher statistics data–simulation comparisons in more $\nu_e$-like regions. Next, these variables are used to train boosted decision trees (BDTs) for the two channels used in the analysis.

The main backgrounds for the $\nu_e$ selections are cosmic-rays, neutrino interactions with $\pi^0$ production, and neutrino interactions (referred to as “$\nu$ other”) that produce charged pions or muons that eventually produce a Michel electron that is mis-identified as an electron produced by a $\nu_e$ interaction. After the full selection dirt events outside the TPC fiducial volume are a negligible contribution.

1. 1eNp0$\pi$ selection

The 1eNp0$\pi$ channel is most sensitive to the eLEE model as it is able to use tracks associated with the vertex in addition to the shower to select electron neutrino events and reject backgrounds. In this selection, two BDTs are trained with XGBoost [62] to separate signal from background: one targets removal of backgrounds that contain a $\pi^0$, and the other backgrounds without $\pi^0$s. Samples of $\nu_e$ events simulated with true neutrino energy below 0.8 GeV are used to define the signal when training the BDTs. Simulated samples with $\nu_\mu$ events from a variety of true interaction categories are used to train the BDT to identify backgrounds. Sixteen topological and calorimetric variables are used to distinguish signal from background in these BDTs. The most important of these are the shower conversion distance, which separates $\nu_e$ from $\pi^0$ events, and the number of distinct branches in the shower, which separates mis-reconstructed $\nu_\mu$ interactions from $\nu_e$-induced showers. The longest track-like particle in the interaction is re-
required to be proton-like which further helps to suppress cosmic-ray backgrounds, $\nu_{\mu}$ backgrounds, and $\nu_{e}$ interactions with final-state charged pions. At pre-selection the purity of the 1$eNp0\pi$ selection is expected to be at the percent level. After the full selection is applied the $\nu_{e}$ purity is expected to be 80% with an efficiency of 15% for true 1$eNp0\pi$ events defined based on the 40 MeV proton energy threshold. The response of the BDT targeting events with $\pi^0$'s is shown in Fig. 5 for the full data-set after the loose selection. The selected sample is obtained by rejecting events with BDT score less than 0.67 and 0.70 for the $\pi^0$ and non-$\pi^0$ BDTs respectively. Relative to pre-selection, cosmic background events are reduced by 99.98% and background events with $\pi^0$'s are reduced by 99.93%. The predicted composition of the selected 1$eNp0\pi$ sample is shown in Table I. The selected $\nu_{e}$ CC events are predicted to be 95% true 1$eNp0\pi$ events, with a $\sim$5% contamination of events with pions.

| 1$eNp0\pi$ Selection |
|------------------------|
| True Category          | Predicted Events |
| $\nu_{e}$ CC 0$\pi_0$ | 0.4 ± 0.1         |
| $\nu_{e}$ CC N$\pi_0$ | 71.7 ± 10.6       |
| $\nu_{e}$ CC X$\pi_0$ | 3.3 ± 0.9         |
| $\nu_{e}$ CC total     | 75.4 ± 11.0       |
| $\nu$ with $\pi^0$    | 5.1 ± 1.4         |
| $\nu$ other            | 5.5 ± 1.1         |
| Cosmic-rays            | 0.8 ± 0.5         |
| Total                  | 86.8 ± 11.5       |

The 1$e0p0\pi$ topology is sensitive to $\nu_{e}$ events in the eLEE model, as well as potentially to single-electron events from a broader range of models. In addition, it complements the 1$eNp0\pi$ selection by mitigating migration effects that may arise from mis-reconstruction or mis-modeling of the multiplicity and kinematics of protons produced by neutrino interactions.

A single BDT is trained to select true 1$e0p0\pi$ events and true 1$eNp0\pi$ events in which protons are not reconstructed. The methods used are the same as those for the 1$eNp0\pi$ selection described in Sec. V C 1, except that only a single BDT is used to reject backgrounds. The BDT leverages 28 topological and calorimetric variables, the most important of which are the measurements of $dE/dx$ which separate electrons from $\pi^0$'s. The BDT response is shown in Fig. 6 for the full data set after applying the loose selection. The final selection is made by requiring events have a BDT score greater than 0.72.

After pre-selection the $\nu_{e}$ purity is estimated to be at the percent level. After the full selection is applied the $\nu_{e}$ purity is expected to be 43% with an efficiency of 9% for true 1$e0p0\pi$ events. The selected $\nu_{e}$ events are predicted to be 70% true 1$e0p0\pi$ events and 30% true 1$eNp0\pi$ events. Relative to pre-selection cosmic background events are reduced by 99.8% and the backgrounds from events with $\pi^0$'s are reduced by 99.7%. Even with this level of $\pi^0$ background suppression, the overall $\pi^0$ contribution to the predicted event rate is, at low energies, comparable to that of electron neutrinos. This is due to the relatively low rate of 1$e0p0\pi$ interactions as well as residual reconstruction limitations. The predicted number of events after the BDT selection is shown in Table II.
TABLE II. Predicted composition of the $1e0p0\pi$ selected events with unconstrained systematic uncertainties in the reconstructed neutrino energy range 0.01–2.39 GeV for 6.86 × 10^{20} POT.

| True Category       | Predicted Events |
|---------------------|------------------|
| $\nu_e$ CC $0p0\pi$ | 8.7 ± 3.0        |
| $\nu_e$ CC N$p0\pi$| 3.8 ± 0.7        |
| $\nu_e$ CC X$pN\pi$| 0.3 ± 0.1        |
| $\nu_e$ CC total   | 12.8 ± 3.4       |
| $\nu$ with $\pi^0$ | 8.6 ± 1.9        |
| $\nu$ other        | 3.1 ± 1.1        |
| Cosmic-rays        | 5.7 ± 1.5        |
| Total              | 30.1 ± 4.3       |

VI. SIDEBANDS AND BLIND-ANALYSIS STRATEGY

This measurement of the $\nu_e$ rate in the BNB and the corresponding exploration of the $\nu_e$ nature of the MiniBooNE excess was designed as a blind analysis, without access to the $\nu_e$ component of the BNB flux. This choice minimizes the risk of bias but also requires careful validation. The flux, cross section, and detector models used in the $\nu_e$ selections are validated using numerous data sidebands, which include samples dominated by $\nu_\mu$ and $\pi^0$ background, as well as the NuMI [63] neutrino beam data. In addition, a small amount of BNB data, less than 10% of the total data set, was fully open during analysis development. Each of these sidebands is described in the following sections, followed by a description of the unblinding procedure. All sidebands are orthogonal with respect to the signal selection.

A. Background-enriched sidebands

Multiple sideband samples were developed to validate the background modeling. Neutral pions are particularly useful as they are both a well-understood standard candle to validate the shower energy reconstruction and an important background for the $\nu_e$ measurement [57]. The area-normalized data to simulation comparison of the reconstructed invariant mass, $M_{\gamma\gamma}$, from $\pi^0 \rightarrow \gamma\gamma$ decays in a high-statistics $\pi^0$ sample is shown in Fig. 7. It demonstrates good reconstruction performance for EM showers and well modeled energy-scale calibration. An additional sideband dominated by neutrino interactions in which a $\pi^0$ is produced was developed by applying the $\nu_e$ selection but requiring that there be at least two reconstructed showers instead of one. This sample is $\pi^0$ rich and is consistent with the $\nu_e$ selections, making this sideband ideal for validating the predicted $\pi^0$ background to the $\nu_e$ measurement. Overall, the prediction was found to be consistent with the observation in $\pi^0$ rich selections, with a trend showing more predicted $\pi^0$ events at higher energies compared to the observation. This trend is accompanied for by the $O(20\%)$ systematic uncertainty associated with pion production in the neutrino interaction model. All inputs to the selection BDTs were checked in this sideband at each selection stage. As an example, Fig. 8a shows events in this sideband that would pass the $1e0p0\pi$ loose selection but have more than one shower. The variable plotted is the shower transverse development angle which parameterizes the shower’s extension into the plane orthogonal to its principal axis.

Sidebands addressing all known major sources of background were obtained by inverting the selection requirement on the BDT scores used by the electron neutrino selections. The result is the definition of separate sidebands for the $1eNp0\pi$ and $1e0p0\pi$ selections. The corresponding datasets were opened progressively: first a “low BDT” sideband, and then an “intermediate BDT” sideband; all input variables were checked in these sidebands. As an example, Fig. 8b shows the distribution of the conversion distance for the reconstructed shower at pre-selection stage for the $1e0p0\pi$ low-BDT sideband. Events with a distance greater than 6 cm between the vertex and the shower are rejected by the loose selection, and the variable is further provided as input to the BDT. Consistency between data and simulation is assessed through quantitative goodness-of-fit tests which show excellent agreement in all sidebands and selection stages, validating the background modeling with high statistics samples.

B. NuMI beam data

Studying $\nu_e$ interactions in data is crucial in order to validate the analysis selection performance and the $\nu_e$ modeling. Measurements of $\nu_e$ interactions on argon...
using the NuMI beamline [63] have been performed by the ArgoNeuT [64] collaboration as well as by MicroBooNE [34, 35]. This makes the NuMI beam data collected at MicroBooNE a well understood sample which is particularly valuable for this validation. Electron neutrinos from NuMI are produced almost entirely from the decay of unfocused kaons at the target, unlike those produced in the BNB which come approximately equally from pion and kaon decays. They reach the MicroBooNE detector at about 27 degrees off the TPC axis and share a similar energy range and peak, around 1 GeV, with the electron neutrinos intrinsic to the BNB, but with a narrower distribution. Results from applying the 1\text{e\nu\!p\!n} and 1\text{e\nu\!p\!n} selections to NuMI data from MicroBooNE’s first year of operations are shown in Fig. 9. Both the 1\text{e\nu\!p\!n} and 1\text{e\nu\!p\!n} channels are predicted to have a \(\nu_e + \bar{\nu}_e\) purity of 87\%. The relatively high \(\nu_e + \bar{\nu}_e\) content of the NuMI beam, 5\% relative to 0.5\% in the BNB, contributes to low predicted background levels in NuMI compared to those predicted in the BNB and makes the NuMI beam insensitive to new electron neutrino signatures in this analysis. The comparable \(\nu_e\) and \(\bar{\nu}_e\) contributions to the NuMI flux, combined with the smaller rate of final-state protons in \(\bar{\nu}_e\) interactions, leads to a \(\sim 40\%\) \(\bar{\nu}_e\) component in the 1\text{e\nu\!p\!n} prediction. In the 1\text{e\nu\!p\!n} channel we observe 16 events with 16.9 predicted, and 54 with 53 predicted in the 1\text{e\nu\!p\!n} channel. The good level of agreement between observed and predicted \(\nu_e\) events on a beamline that has been used for multiple \(\nu_e\) cross section measurements on argon provides a strong validation of the selection’s ability to identify electron neutrinos in data.

C. Progressive data opening for BNB events

A small dataset was fully open during the development of this analysis: \(4 \times 10^{19}\) POT from the first period of data taking and \(1 \times 10^{20}\) POT from the third period of data taking. Together these correspond to less than 10\% of the full \(6.86 \times 10^{20}\) POT used for the results presented in this article. This small open dataset was first used to develop and test the MicroBooNE LArTPC event reconstruction. It was also used to validate agreement between data and simulation during analysis development, where all inputs to the BDTs and other variables of physics interest were cross-checked at each selection stage. After the selections were frozen and validated in sideband data the analysis was tested with several fake data sets. These were created with and without an injected electron-like signal as well as with simulation modifications. Results with the frozen analysis on these fake data sets were found to be consistent with the true injected signal. Unblinding was performed in stages moving progressively from background-enriched sidebands and high-energy \(\nu_e\) regions towards the low-energy region in the BNB where the eLEE signal is predicted according to the model described in III D. This was done in three energy regions. The high-energy region was defined as \(E_{\text{reco}}^{\nu_e} > 0.85\) \((0.90)\) GeV for the 1\text{e\nu\!p\!n} \((1\text{e\nu\!p\!n})\) selection, the medium-energy region as \(E_{\text{reco}}^{\nu_e} > 0.65\) GeV for both selections, and the low-energy region as \(E_{\text{reco}}^{\nu_e} > 0.15\) GeV for both selections. Selection criteria, including BDTs, were frozen before opening the first high-energy \(\nu_e\) sideband. Following the opening of the medium and high energy regions, goodness-of-fit \(p\)-values of 0.277, 0.206, and 0.216 were measured respectively for 1\text{e\nu\!p\!n} events, 1\text{e\nu\!p\!n} events, and the two combined. These are obtained comparing the observed data to the prediction from simulation after applying the

FIG. 8. Example distributions of BDT input variables in sideband regions.
\( \nu_{\mu} \) constraint procedure described in the next section. The level of consistency with the underlying prediction supported the decision to move forward with unblinding the full energy range.

**VII. SYSTEMATICS AND APPLICATION OF THE \( \nu_{\mu} \) CONSTRAINT**

We separate the sources of systematic uncertainty into three main categories: flux, cross section, and detector response uncertainties. Details about variations for each of these categories are presented in Sec. III. Uncertainties associated with the statistics of the simulation samples used in the analysis are also included. Uncertainties related to the flux, particle propagation, and, partially, cross section are assessed through multi-universe simulations which are generated by varying the underlying model parameters within their range of uncertainty. Detector response and several cross section model uncertainties are assessed through single variations of the underlying simulation model, referred to as uni-sims. Systematic uncertainties are included in the analysis through the formalism of the covariance matrix:

\[
C_{\text{Syst}} = C_{\text{Flux}} + C_{\text{XSec}} + C_{\text{Detector}} + C_{\text{MCstat}}
\]

\[
C_{ij} = \frac{1}{N} \sum_{k=1}^{N} \left( n_{i}^{k} - n_{i}^{\text{CV}} \right) \left( n_{j}^{k} - n_{j}^{\text{CV}} \right),
\]

where \( C \) indicates a covariance matrix, \( i, j \) are indices over histogram bins, \( n_{i}^{\text{CV}} \) is the nominal (central value) bin content, \( n_{i}^{k} \) is the content of the ith bin in the alternative universe \( k \), and \( N \) is the total number of alternative universes. Uni-sim variations are symmetrized in the covariance matrix approach adopted in the analysis.

Uncertainties are constrained by leveraging the correlations between \( \nu_{\mu} \) and \( \nu_{e} \) events, which share common flux parentage in their decay chain in the beamline and significant overlap in the cross sections that govern their interaction rate and final-state kinematics. Through correlations for shared sources of modeling uncertainty, the high-statistics measurement of \( \nu_{e} \) (see Sec. V B) is used to update the \( \nu_{e} \) prediction and constrain the total systematic uncertainty. When considering all uncertainties (cross-section uncertainties only), the level of correlation between \( \nu_{\mu} \) and \( \nu_{e} \) events in the signal region is 60% (80%). Throughout this analysis, the \( \nu_{\mu} \) flux is assumed to be unoscillated.

The \( \nu_{\mu} \) constraint is implemented by relying on the covariance between \( \nu_{\mu} \) and \( \nu_{e} \) bin contents, the predicted bin content in the different channels, and the observed \( \nu_{\mu} \) data, and leveraging the properties of block matrices [65]. Given the bin-to-bin covariance matrices for the \( \nu_{\mu} \) channel (\( C_{\nu\mu}^{\nu\mu} \)), \( \nu_{e} \) channel (\( C_{\nu\mu}^{\nu e} \)), and the covariance between the two channels (\( C_{\nu\mu}^{\nu\nu} \)), the predicted bin content in each bin \( i \), \( m_{i}^{\nu} \) and \( m_{i}^{\nu_{\mu}} \) for \( \nu_{e} \) and \( \nu_{\mu} \) respectively, and the \( \nu_{\mu} \) observed bin contents \( n_{i}^{\mu} \), the constrained \( \nu_{e} \) prediction is expressed as:

\[
m_{e}^{\text{constrained}} = m_{e}^{\nu_{e}} + C_{e
u}^{\nu_{\mu}} (C_{\nu\mu}^{\nu\nu})^{-1} (n_{e}^{\nu_{\mu}} - m_{e}^{\nu_{\mu}}),
\]

and the constrained covariance matrix as:

\[
C_{\text{e\nu constrained}} = C_{e\nu}^{\nu} - C_{e\mu}^{\nu\mu} (C_{\nu\mu}^{\nu\nu})^{-1} C_{\nu\mu}^{\nu\mu}.
\]

The fractional systematic uncertainty is presented in Fig. 10 for the three channels included in this analysis (\( \nu_{\mu}, 1eNp0\pi, \) and \( 1e0p0\pi \)). The \( \nu_{\mu} \) selection has no requirement on hadron multiplicity, so the data it selects can constrain both the \( 1eNp0\pi \) and \( 1e0p0\pi \) prediction. This selection aims to maximize the reduction of flux uncertainties, particularly at low reconstructed neutrino en-
ergy. Overall, the constraint reduces the systematic uncertainties in the electron neutrino selections by 10–40% relative to the pre-constraint uncertainties. In the analysis, the $\nu_\mu$ constraint is performed on distributions of the $\nu_\mu$ and $\nu_e$ reconstructed neutrino energy and applied to all quantitative results presented in the next section.

VIII. RESULTS

We first present results from the $\nu_e$ selections to test the agreement between the observation and neutrino interaction model prediction and then the tests of the eLEE hypothesis, the $\nu_\mu$ relative to the pre-constraint uncertainties. In the analysis, the $\nu_e$ selections to test the constraint is performed on distributions of the $\nu_\mu$ and $\nu_e$ reconstructed neutrino energy and applied to all quantitative results presented in the next section.

A. Modeling of electron neutrinos

The observed $1eNp0\pi$ and $1e0p0\pi$ event rates are plotted as a function of reconstructed energy in Fig. 11, where data is compared to the prediction after the $\nu_\mu$ constraint. Given the agreement observed with the $\nu_\mu$ selection (Fig. 4), the effect of the constraint procedure on the $\nu_e$ prediction is relatively small (less than 10%).

The first statistical test performed is a goodness of fit to quantify how well the intrinsic $\nu_e$ model matches the data in reconstructed neutrino energy. The results are presented in Table III. The data are consistent with the intrinsic $\nu_e$ model with $p$-values of 0.182, 0.126, and 0.098 for $1eNp0\pi$ events, $1e0p0\pi$ events, and the two combined, respectively.

| Channel | $\chi^2$ | $\chi^2$/dof | $p$-value |
|---------|---------|-------------|----------|
| $1eNp0\pi$ | 15.2    | 1.52        | 0.182    |
| $1e0p0\pi$ | 16.3    | 1.63        | 0.126    |
| $1eNp0\pi + 1e0p0\pi$ | 31.50   | 1.58        | 0.098    |

Electron neutrino events can be further characterized in terms of their kinematics. Figure 12 shows the angle ($\theta$) of the reconstructed electron candidate relative to the beam direction and the kinetic energy of the leading proton for $1eNp0\pi$ events. Considering only normalization, in the 0.15-1.55 GeV range, 53 events are observed by the $1eNp0\pi$ channel with a constrained prediction of 78.9 ± 11.6 events, corresponding to a deficit of 1.7$\sigma$. The deficit is most pronounced at intermediate energies and in the forward direction. As demonstrated by the p-value obtained by the goodness of fit test, the estimated combined statistical and systematic uncertainties accommodate the observed difference.

In the $1e0p0\pi$ channel we observe good overall normalization agreement between data and simulation, with 31 events observed compared to a constrained prediction of 27.8 ± 4.4, but the simulation under-predicts the data in the energy bins corresponding to $0.15 < E_{\text{reco}} < 0.43$ GeV. In multiple $\pi^0$ enriched sideband regions, however, the data is consistent with the prediction within statistical and systematic uncertainties as reported in Sec. VI. In the $0.15 < E_{\text{reco}} < 0.43$ GeV energy bins of the NuMI sideband, the high electron neutrino purity and satisfactory agreement between data and simulation validate the interaction model for low energy electron neutrinos. We find that data events in this range are dominated by single-shower events with a d$E$/d$x$ profile consistent with a minimum ionizing particle, as expected for both signal and most surviving background events from simulation. Figure 13 shows the angular distribution of $1e0p0\pi$ events, both over the full energy range and in the region corresponding to $0.15$–$0.43$ GeV. Integrated over the full energy range, the angular distribution shows good agreement with simulation. In the low energy bins, where the simulation under-predicts the observed data, events primarily populate the region with $\cos \theta > 0$. More data will be needed to further study these events. The observation of good shape agreement between the data and the prediction in the leading proton kinetic energy distribution shown in Fig. 12b, as well as a visual scan of selected events, suggests that the migration between the $1eNp0\pi$ and $1e0p0\pi$ selections is minimal.
FIG. 10. Summary of the impact of systematic uncertainties presented in Sec. III for all selected events in the three channels used in the analysis, shown in the 0.15–1.55 GeV energy range that is used for quantitative results. The percent systematic uncertainty by channel is shown in the top panel. The individual unconstrained contributions coming from flux, cross section, and detector plus simulation statistics are shown in blue, orange, and green respectively. Detector uncertainties account for both Geant4 re-interaction and detector response modeling uncertainties. The total unconstrained systematic uncertainty is in black and, for the 1eNp0π and 1e0p0π selections, a grey area indicates the total constrained uncertainty. The νμ uncertainties are not changed by the constraint. In the high energy region of the 1e0p0π energy spectrum, where we have very few events, the uncertainties grow up to O(100%).

FIG. 11. Reconstructed neutrino energy for the selected 1eNp0π (a) and 1e0p0π (b) events. The pre-constraint number of predicted events is shown broken down by true interaction topology. The constrained prediction using the muon neutrino data is also shown both with (red) and without (black) the eLEE model included. Systematic uncertainties on the constrained prediction are shown as a shaded band. While not shown in the figure, systematic uncertainties on the eLEE model are considered in the analysis. Quantitative results are calculated in 10 bins from 0.15 to 1.55 GeV, shown here starting in the second bin. The lower bound of the first bin is 0.01 GeV.

B. Test of the eLEE model

The statistical tests performed to assess the probability that the eLEE model introduced in Sec. III is present in the data are described in this section. The first is a simple hypothesis test in which two hypotheses are tested in order to assess the probability of rejecting one hypothesis assuming the other is true. The hypotheses tested are the intrinsic νe prediction (H₀) and the intrinsic νe prediction plus the eLEE model contribution (H₁). The result reported from this test is the p-value based on the Δχ^2 between H₀ and H₁ defined as:

\[
\Delta \chi^2 = \chi^2 (H_0) - \chi^2 (H_1).
\]  

The expected sensitivity and the data results are presented in Fig. 14 and summarized in Table IV. In the 1eNp0π channel, the data are consistent with H₀ with a p-value of 0.285, which corresponds to 28.5% of the
toy experiments that assume $H_0$ is true showing a $\Delta \chi^2$ smaller than the observed value. When the inverse test is performed, with toy experiments assuming $H_1$ is true, we find a p-value of 0.021 thus implying that the 1eNp0π channel alone excludes the $H_1$ hypothesis at the 97.9% confidence level (CL). In the 1e0p0π channel, as shown in Fig. 14b, the observed $\Delta \chi^2$ falls in the tail of the expected distribution from both hypotheses. The observation indicates a preference for the $H_1$ over the $H_0$ hypothesis with a fraction of toys in the tail of 0.072 for $H_1$ and of 0.016 for $H_0$. While the combined results are expected to be driven by the larger sensitivity of the 1eNp0π channel to the model tested, the preference for $H_1$ in the 1e0p0π channel leads to an intermediate result between the two hypotheses.

The Feldman-Cousins procedure [67] is used to test the signal-strength $\mu$, where $\mu$ is a flat scaling parameter of the eLEE model, and is intended to provide further quantitative insight into a possible signal enhancement at low energy. Toy experiments are generated for different values of true signal-strength $\mu$. In this test the metric for defining the ordering rule based on the likelihood ratio $R(x|\mu)$ is approximated as

$$ R(x|\mu) \sim \Delta \chi^2 (x|\mu) = \chi^2(x, \mu) - \chi^2(x, \mu_{BF}) $$

where $\mu_{BF}$ is the value of $\mu$ that maximizes the likelihood ratio for a given toy-experiment $x$. Given the observed data, $\chi^2(data, \mu)$ values are computed for all values of $\mu$ and the best-fit value is identified. Confidence intervals are extracted based on the fraction of the toy experiments that give a larger $\Delta \chi^2 (x|\mu)$ than $\Delta \chi^2 (data|\mu)$. Results are shown in Fig. 15. Intervals at the 90% CL are reported in Table V where the best-fit value $\mu_{BF}$ and the expected sensitivity are also reported. In the 1eNp0π

(a) Electron angle relative to beam direction.
(b) Proton kinetic energy.

FIG. 12. Selected kinematic distributions for events that pass the 1eNp0π selection. Expected events and uncertainties are shown as predicted by the nominal simulation.

(a) All selected events.
(b) Low energy selected events from 0.15–0.43 GeV.

FIG. 13. Selected 1e0p0π events as a function of electron angle with respect to the beam. Expected events and uncertainties are shown, without the $\nu_\mu$ constraint applied.
TABLE IV. Summary of the simple hypothesis tests. Reported p-value($H_0$) (p-value($H_1$)) results reflect the probability for the $H_0$ ($H_1$) hypothesis to give $\Delta \chi^2 = \chi^2(H_0) - \chi^2(H_1)$ smaller than the observed value. The observed value of $\chi^2(H_0)$ is reported in Table III. The median sensitivity in terms of these p-values is also reported under the assumption that the eLEE model $H_1$ (no-signal scenario $H_0$) is true. The fraction of toy experiments generated under the $H_0$ hypothesis with $\Delta \chi^2$ larger than the median value obtained for the eLEE model $H_1$ is $1 - p$-value($H_0$) so the combined $1eNp0\pi + 1e0p0\pi$ median sensitivity to reject $H_0$ if $H_1$ is true is 0.032.

| Channel         | obs. $\Delta \chi^2$ | obs. p-value($H_0$) | obs. p-value($H_1$) | $p$-value($H_0$) | $p$-value($H_1$) | Sensitivity | Sensitivity |
|-----------------|-----------------------|---------------------|---------------------|-----------------|-----------------|-------------|-------------|
| $1eNp0\pi$      | -3.89                 | 0.285               | 0.021               | 0.957           | 0.061           |             |             |
| $1e0p0\pi$      | 3.11                  | 0.984               | 0.928               | 0.759           | 0.249           |             |             |
| $1eNp0\pi + 1e0p0\pi$ | -0.58                 | 0.748               | 0.145               | 0.968           | 0.049           |             |             |

FIG. 14. Results for the simple hypothesis test in the $1eNp0\pi$ (a), $1e0p0\pi$ (b), and combined (c) channels. The $\Delta \chi^2$ between the intrinsic $\nu_e$ model and the eLEE hypotheses is plotted for toy experiments generated with these hypotheses. The $p$-values indicate the fraction of toy experiments with $\Delta \chi^2$ smaller than the observation. The median $p$-value for toy experiments produced assuming the intrinsic $\nu_e$ model is also reported.

We observe that $\mu_{BF}$ is 0, and values of $\mu > 0.82$ are excluded at the 90% CL. Due to the low sensitivity to the eLEE model in the $1e0p0\pi$ channel we find that the 90% confidence interval covers a wide range of $\mu$ values, from 1.1 to 15.0. The combined measurement excludes $\mu > 1.57$ at the 90% CL.

Overall, the data are consistent with the intrinsic $\nu_e$ model, as shown in Sec. VIII A, but an enhancement of the event topologies measured in the $1e0p0\pi$ channel cannot be ruled out. The data in the separate $1eNp0\pi$ and $1e0p0\pi$ channels suggest that a simple energy-dependent scaling of the $\nu_e$ beam content as defined in the eLEE model tested is not favored.

IX. CONCLUSIONS

This article presents a measurement of charged current $\nu_e$ interactions without final-state pions in the MicroBooNE detector from the Fermilab BNB. This analysis incorporates numerous sidebands to validate the modeling of the detector response as well as the neutrino flux and interaction model. Good compatibility between data and simulation is found in all validation data sets, including the $\nu_\mu$ selection used to constrain the flux and cross section uncertainties of the intrinsic electron neutrino interactions. Electron neutrino interactions are observed with high purity leveraging the power of the MicroBooNE LArTPC detector and are found to be consistent with the $\nu_e$ prediction through a goodness of fit test at the 10–20% level. These events are further characterized using their measured kinematic properties of electron angle and kinetic energy of the leading proton.

Comparison to a signal model based on the median MiniBooNE eLEE observation is also studied. When the presence of the eLEE model is tested against the intrinsic electron neutrino interaction model, data in the two channels combined ($1e0p0\pi + 1eNp0\pi$) does not indicate a strong preference between the two hypotheses. The eLEE signal model is disfavored by the $1eNp0\pi$ channel at the 97.9% CL. The eLEE model is further parametrized in terms of the signal strength $\mu$, and confidence intervals for this parameter are extracted with the Feldman-Cousins procedure. The $1e0p0\pi$ selection,
TABLE V. Best-fit eLEE model signal strength ($\mu$) and 90% confidence intervals. The sensitivity is quantified by reporting the expected upper limits assuming $\mu = 0$.

| Channel          | Data $\mu_{BF}$ | 90% CL interval on $\mu$ | 90% upper limit on $\mu$ |
|------------------|-----------------|----------------------------|--------------------------|
| 1eN0p0π          | 0.00            | [0.00, 0.82]               | 1.16                     |
| 1e0p0π           | 4.00            | [1.13, 15.01]              | 3.41                     |
| 1eN0p0π + 1e0p0π | 0.36            | [0.00, 1.57]               | 1.07                     |

![Graph](image)

FIG. 15. Results for the signal strength test in the 1eN0p0π (a), 1e0p0π (b), and combined (c) channels. The $\Delta \chi^2$ as a function of the signal strength is evaluated with respect to the best-fit signal strength value. The observed confidence interval at 90% confidence level is indicated with a vertical lines, as well as the expected upper limit in case of no signal.

which is overall less sensitive to the eLEE model, observes more events than predicted in the lowest energy region and we find that the 90% confidence interval covers a wide range of $\mu$, with a lower bound of 1.1. The 1eN0p0π selection, which drives the analysis sensitivity due to its higher statistics and purity, indicates a preference for no excess of low-energy electron neutrinos with respect to the intrinsic beam content prediction resulting in an upper 90% CL limit on the signal strength of 0.82. More data and tests of additional models will provide further insight into these results.

This analysis is part of a broad effort by the MicroBooNE collaboration to measure low-energy electromagnetic interactions. It will be followed by additional analyses, including those which use the full MicroBooNE dataset, roughly twice the size of that used in this result as well as advances in low energy shower reconstruction and analysis tools. Finally, the full SBN program [68], with the introduction of a near detector and a third detector at a longer baseline, will further expand this investigation.

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