MICROBOONE-NOTE-1074-PUB

Neutrino Interaction Model and Uncertainties for MicroBooNE Analyses

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May 2020

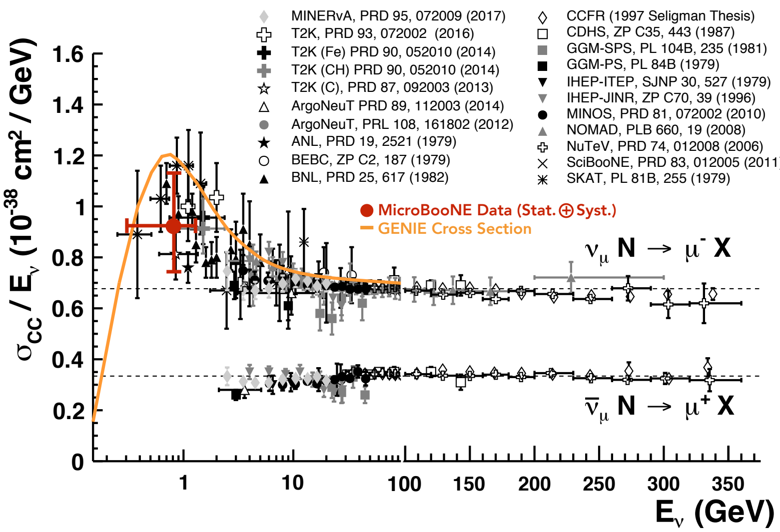
Abstract

The MicroBooNE experiment is searching for an excess of electron-like events at low neutrino energy, as well as making the first high-statistics measurements of neutrino interactions on argon. Interpretation of these results requires a reliable model of neutrino interaction physics with well-motivated uncertainties. This note describes the neutrino interaction model and uncertainties adopted for use in MicroBooNE's cross section measurements and low-energy excess search.

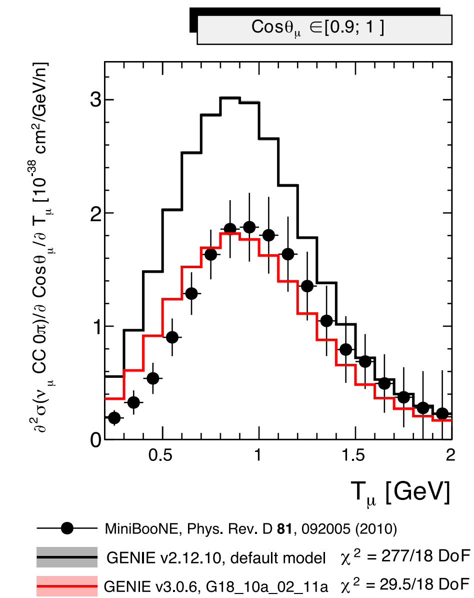
Contents

1 Overview

A fundamental challenge in MicroBooNE [1] — and the low-energy excess (LEE) search in particular — is the lack of direct experimental constraints on low-energy neutrino interactions with argon nuclei. It is important to note that any "excess" must be defined relative to what is known about neutrino interactions, including uncertainties. Data from T2K and MiniBooNE are valuable because the beam energy is similar, but their measurements are on a carbon target, and we must still rely on models to extrapolate predictions to argon. Although the cross section uncertainties currently implemented for the default GENIE model set are around 20% for ν-Ar scattering at $E_\nu \sim 200$ MeV, this is not necessarily representative of our lack of knowledge in the extrapolation of models from higher energies and other targets. Figure 1 (left) summarizes existing neutrino charged-current inclusive ν_μ and $\bar{\nu}_\mu$ cross section measurements, overlaid with predictions according to a specific model. This includes a single data point (in red) from MicroBooNE's CC-inclusive measurement [2] [3].



(a) ν_μ and $\bar{\nu}_\mu$ CC inclusive total cross section measurements



(b) MiniBooNE CC0π differential cross section

Figure 1: LEFT: ν_μ and $\bar{\nu}_\mu$ CC inclusive total cross section measurements, with the GENIE v2.12.2 prediction overlaid (note that this is not the GENIE prediction we now use in MicroBooNE: current analyses use GENIE v3.0.6 G18_10a_02_11a) and MicroBooNE measurement shown in red (Figure from [2]). RIGHT: MiniBooNE CC0π differential cross section for muon kinetic energy T_μ at a forward angle compared with GENIE v2 and v3 simulations.

Recent theoretical work as well as detailed experimental measurements from, e.g., MINERvA and T2K [4, 5, 6, 7, 8, 9, 10] have informed further development of neutrino interaction models in the modern event generator packages used at accelerator energies (GENIE [11], GiBUU [12], NEUT [13], and NuWro [14]). The GENIE models [15] described in this note have been previously validated against bubble chamber experiments (many targets), and recent $CC0\pi$ cross section data from MiniBooNE [16]. An example of the MiniBooNE differential cross section is given in Fig. 1b together with predictions from versions 2 and 3 of GENIE (see Sect. 2.2 for more detail about the differences between these two GENIE model sets). It is important to note that MicroBooNE has adopted the new GENIE nuclear/QE/MEC models [17] that are more suitable for low neutrino energy experiments. This provides an excellent basis for a more complete fit. The cross section models, parameter central values, and (correlated) uncertainties must be chosen based on our best understanding of the available scattering data. In cases where cross sections are poorly constrained in our kinematic regions of interest, we can choose to assess theoretically-motivated uncertainties that we believe provide sufficient coverage.

This document introduces the neutrino interaction models, parameter central values, and systematic uncertainties used in the configuration of GENIE (v3.0.6 G18_10a_02_11a) adopted by MicroBooNE for the analyses presented at Neutrino2020. The exact way the cross-section model (and uncertainties) impacts an analysis will depend on the analysis itself. In general, cross-section measurements use simulation to estimate the efficiency and distribution of backgrounds in a selected event sample. The background events are then subtracted from the selected events to provide an estimated signal-event distribution in data, and the efficiency is used to correct that distribution. Therefore, a cross-section measurement requires a model that can provide a reliable estimate of the backgrounds in a selection (although of course, this can be mitigated by selection cuts and the use of data-driven background estimation with sidebands), but the key requirement is for the model to simulate data closely enough that we can trust the efficiency estimation. MicroBooNE's low-energy excess search (LEE), on the other hand, does not measure a cross section. Instead, it relies on the model to provide a reasonable baseline for any non-LEE contributions to the measured distributions - both yields and estimated uncertainties. The models also correlate uncertainties between different samples of selected events. For example, the electron-like LEE search uses a selection of charged-current muon neutrino interactions to constrain the flux and cross-section, in order to accurately predict a sample of charged-current electron neutrino interactions. This requires particular focus on the models at low energy, and the models' predicted relationship between ν_e and ν_μ interactions. It also requires that the uncertainties are sufficient that most data are within 1σ of the prediction, such that the constraint can work as intended.

The material presented in this note can be broken up into two categories: the 'central value' GENIE prediction and the uncertainty on that prediction (which is described here in terms of uncertainties on the individual model parameters). MicroBooNE is the first experiment to move to GENIE v3 as its central value Monte Carlo prediction, and we found early on from internal data-MC comparisons that the simulation under-predicted the data in the CC0π channel (see section 2.1 for an explanation of channels and models discussed in this article). Comparisons to data from other neutrino experiments showed the same problem in predicting T2K CC0π data, which has a neutrino flux in a very similar range to MicroBooNE. Because of this, we decided it was necessary to retune the GENIE CCQE and CCMEC models for MicroBooNE analyses, using T2K CC0π data to do so (to avoid any potential biases from tuning to our own data). Section 3 describes the T2K data used for the tune, the result of the tuning procedure (a preliminary "MicroBooNE tune"), and comparisons of this preliminary tune to data from the T2K, MINERvA, and MiniBooNE experiments. Unfortunately a bug was found in one of the parameters used for the tune (see discussion in section 3.3), and therefore this tune is to be considered preliminary; it will be updated in the near future.

The CCQE and CCMEC models were considered in the tuning procedure because we saw the largest difference between data and simulation in the CC0π channel, and there has been significant uncertainty about these models in the theoretical community. These channels are also particularly important for MicroBooNE's low-energy excess searches because they dominate the CC-inclusive cross section at low energies. Tuning other channels (e.g. CCRES, NC) is not a high priority at this time, either because we do not see large discrepancies in these channels (in MicroBooNE data or in the external data comparisons shown in section 3.3.1), or because the modeling of these channels is not of particular concern in current MicroBooNE analyses. Therefore, for these channels we take the GENIE v3.0.6 G18_10a_02_11a prediction. We may, however, extend the work presented here to include tuning of other channels in the future.

Section 4 describes the uncertainties we assign to our GENIE models. For those parameters included in the tuning, our uncertainty estimation is guided by the tuning results. For those parameters where we take the GENIE v3.0.6 G18_10a_02_11a models as they are, we also take the model uncertainties provided by the GENIE collaboration, which are based on tuning and comparisons to neutrino scattering data and we do not see strong evidence of a need to change them. One exception to this is the CCMEC model: GENIE v3.0.6 G18_10a_02_11a uses the Valencia MEC model [18, 19, 20], but does not provide any official reweighting tools. In this case, MicroBooNE has internally developed a nearly comprehensive set of tools to assign uncertainties to the Valencia model by reweighting. In the absence of data to constrain the model, we take conservative uncertainties on all parameters.

Section 5 presents the energy-dependent total cross sections predicted by the preliminary "MicroBooNE tune" of GENIE for CC inclusive scattering of ν_μ and ν_e on ^{40}Ar. Several alternative models of these cross sections are compared and largely found to give low-energy predictions that lie within our estimated 1σ uncertainty band. Coverage of the alternative models is poorer in the mid-hundreds of MeV region, partially due to the bug mentioned previously.

2 Existing central value models in GENIE

2.1 A note on models and acronyms

This note describes the models used to simulate neutrino interactions in MicroBooNE. Interactions can be broadly classified as describing charged-current (CC) or neutral-current (NC) scattering. Several acronyms are often used in this note when describing specific interaction processes:

- QE: Quasielastic scattering, in which the neutrino interacts with a single nucleon, and only a lepton and a single nucleon are produced.
- RPA: A correction to the CCQE cross section that accounts for nuclear screening due to long-range nucleon-nucleon correlations. This is an important and somewhat uncertain component of any QE model. The acronym RPA stands for Random Phase Approximation, the method by which the correction is calculated.
- MEC: used in this note to denote processes in which the neutrino interacts with a correlated pair of nucleons, often referred to as "2p2h" scattering. It is similar to QE scattering from a correlated pair of nucleons. The acronym stands for "Meson Exchange Currents", a mechanism in which two nucleons are bound together by exchange of a meson.
- RES: resonant scattering, or resonance production. In most of the models described in this document, this refers to cases in which the neutrino interaction produces a Δ or N* resonance that may decay to produce a pion in the final state.
- DIS: Deep Inelastic Scattering, in which the neutrino interacts with a subcomponent of a nucleon, rather than the nucleon as a whole. The model described in this document extends down to pion production threshold and therefore is supposed to give a good representation of nonresonant pion production.
- COH: Coherent scattering, in which the neutrino interacts with an entire nucleus, rather than an individual nucleon, and the nucleus is left in the ground state after interaction.
- FSIs: Final State Interactions, referring to interactions of the hadrons coming out of the initial neutrino interaction, before they exit the nucleus.

Many neutrino experiments define their measurements in topological terms, describing the particles detected. An example of this would be CC0π, indicating a charged lepton but no pions (specifically no pions above detection threshold) in the final state. Topological definitions can map to multiple interaction processes thanks to FSIs and detection thresholds. For example, the CC0π signal can include contributions from CCQE, CCMEC, and CCRES/CCDIS in which a pion is produced and subsequently absorbed in the target nucleus.

2.2 GENIE models

A variety of CC neutrino differential cross section data for low neutrino energy has been published from MiniBooNE [16] and T2K [4]. The MiniBooNE data prompted significant theoretical activity to better describe it. GENIE v2 used models that were derived for higher energy, e.g. the relativistic Fermi gas nuclear model and Llewellyn-Smith QE model. For recent MicroBooNE work, we switch to GENIE v3. The model set used includes the full Valencia model [17, 21, 20] for the local Fermi gas nucleon momentum distribution, CCQE, and CCMEC interactions. The new model set also has improved FSI and pion production treatments. Fig. 1b shows a comparison of MiniBooNE CC0π data with simulations from these two models. GENIE v3 has a clear advantage and will be the basis for the fit we describe in this document.

3 Tuned Central-Value Prediction

MicroBooNE has recently updated its simulation to use the most up-to-date GENIE predictions, from GENIE v3.0.6 G18_10a_02_11a [15]. These new models contain physics that is believed to be more correct than GENIE v2.12.2 (used in previous MicroBooNE analyses) because the models were developed [22] to give good agreement with the MiniBooNE CC0π data set. This version of GENIE was chosen in part because of the good agreement with MicroBooNE's published CC-inclusive cross-section measurement [3]: for 42 bins, the χ^2 between data and simulation is 214 for GENIE v2.12.2, and 105 for GENIE v3.0.6 G18_10a_02_11a.

However, comparisons to MicroBooNE data, as well as published data from T2K and MiniBooNE (see Section 3.3.1), show that the simulation underestimates the data, particularly in pion-less (CC0π) interactions at low energy. To mitigate this underprediction, fits to T2K CC0π cross-section data [4] were performed to tune parameters within this model, as described in this section. The result of the fitting procedure is a preliminary tune of GENIE. The fitting results are shown in Section 3.3, and comparisons of this preliminary tune to published data sets are shown in Section 3.3.1. When including uncertainties on the fit parameters, this new tune shows good agreement with MicroBooNE data, as shown in Figure 6.

The tuning studies were performed using the NUISANCE software package [23], and we are very grateful to the NUISANCE developers (particularly L. Pickering and C. Wret) for their support for this work.

3.1 T2K Datasets

We perform fits to T2K CC0π cross section data, published in [4]. The paper includes two analyses, which both use the same data events but apply different selection cuts and extract the cross section using different methods:

- **Analysis 1:** Uses a binned likelihood fit performed simultaneously in four signal and two control regions to extract the cross section. A 2D double-differential cross section as a function of muon momentum (p_μ) and angle ($\cos\theta_\mu$) is provided in the full phase space.
- **Analysis 2:** Uses Bayesian unfolding to extract the cross section. A 2D double-differential cross section as a function of muon momentum (p_μ) and angle ($\cos\theta_\mu$) is provided in restricted phase space: $p_\mu > 0.2$ GeV, $\cos\theta_\mu > 0.6$.

For the tuning presented here, we fit to "Analysis 1" from the paper and use comparisons to "Analysis 2" as a cross-check.

Figure 2 shows the T2K CC0π analysis 1 data compared to our nominal GENIE model. We see the general pattern that GENIE under-predicts the T2K data, as we have also seen in MicroBooNE. T2K provides a double-differential cross section as a function of muon momentum (p_μ) and angle ($\cos\theta_\mu$). This is projected in these figures onto a 1D histogram as a function of bin number, where the bin number loops over muon momentum in slices of fixed muon angle. We show backward-angle data in lower bins and forward-angle data in higher-numbered bins. For example, bins 1 - 2 in figure 2 are bins in p_μ ranging from 0 to 0.4 GeV, for the single angle bin $-1.0 < \cos\theta_\mu < 0$. Bins 3 - 6 are bins in p_μ ranging from 0 to 0.6 GeV, for the single angle bin $0 < \cos\theta_\mu < 0.6$.

The T2K data include bins in muon momentum up to 30 GeV. There is almost no cross section for a neutrino beam peaking at 600 MeV to produce a 30 GeV muon, and indeed we see very small cross sections measured in these bins. With the cross section in these bins being so small, there is concern that a small change in these bins could cause a large change in the χ^2, and that these bins could drive the fit in an undesirable way. In addition, we are not concerned with the modelling of 30 GeV muons in MicroBooNE, and so we cut the high-momentum bins out of the fits presented here. That means masking bins with $p_\mu >$ around 2 GeV (exact value depends on the specific $\cos\theta_\mu$ bin, with binning shown in [4]).

3.2 Fitting Procedure

The T2K data were fit using the NUISANCE software package [23]. NUISANCE allows fitters to take the published bin-to-bin covariance matrix into account when fitting, and doing a fit in this way is generally regarded as the correct way to fit the data. Unfortunately, attempts to fit the T2K data with the full covariance matrix proved problematic, resulting in a significant and unphysical reduction of the cross section across all of the bins. Multiple hypotheses have been considered to explain this observation, including model-dependence in the published data/covariance matrices in a way that will not allow a satisfactory fit with GENIE, or a manifestation of Peelle's Pertinent Puzzle [24]. We note that a recent publication in which NuWro models are fit to T2K and MINERvA data sees a similar effect when fitting the MINERvA data and also attributes it to Peelle's Pertinent Puzzle [25].

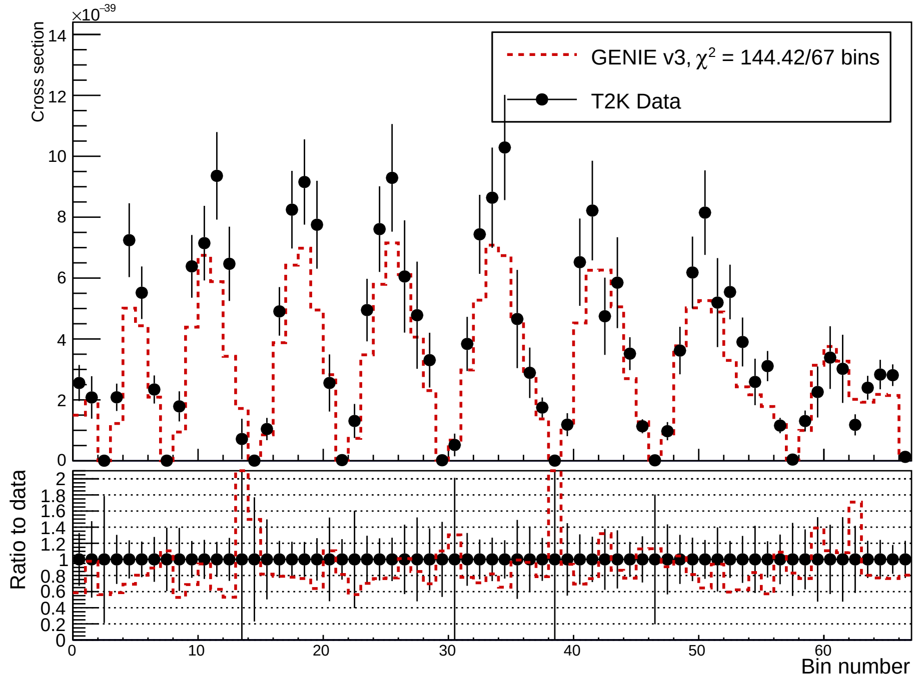


Figure 2: Comparison of nominal GENIE v3.0.6 G18_10a_02_11a to T2K CC0π data: analysis 1. Note that this is a plot that collapses 2D momentum-angle distributions into a single histogram: we show backward-angle data in lower bins and forward-angle data in higher numbered bins. See text for details.

To avoid these problems, we proceed with fits that do not use the full covariance matrix, but instead use only diagonal elements – corresponding to the error bars on each data point drawn in Figure 2 – and do not consider correlations between bins. We find that this fitting method gives satisfactory results.

3.3 Tuning results

Our strategy is to fit model parameters in the GENIE CCQE and CCMEC models to the T2K CC0π analysis 1 data, without using the covariance matrix, and masking the overflow bins that go to $p_\mu = 30$ GeV. As previously discussed, we use only diagonal elements of the published uncertainty covariance matrix to evaluate the χ^2 that is minimized in the fit. Because MINUIT fits can be slow and sometimes unreliable with large numbers of parameters, we limit the number of parameters we fit to four, and choose the CCQE and CCMEC model parameters that we find to have the largest effect on the prediction. The chosen parameters are:

- **MaCCQE:** Axial mass in the dipole form factor for CCQE interactions
- **CCQE RPA:** Parameter that changes the strength of the Nieves RPA correction to the CCQE cross section, from the full Nieves correction (parameter value = 0) to no RPA correction (parameter value = 1). This parameter is not available in default GENIE v3.0.6, and was added by MicroBooNE to enable a more complete estimate of cross-section uncertainties. See Section 4.1 for more details.
- **CCMEC Normalization:** Parameter controlling the normalization of CCMEC interactions. This parameter is not available in default GENIE v3.0.6, and was added by MicroBooNE to enable a more complete estimate of cross-section uncertainties. See Section 4.1 for more details.
- **CCMEC Cross-section Shape:** Parameter that is intended to change the CCMEC cross section shape from the Nieves prediction (parameter value = 0) to the shape predicted by GENIE's Empirical MEC model (parameter value = 1). This parameter is not available in default GENIE v3.0.6, and was added by MicroBooNE to enable a more complete estimate of cross-section uncertainties. See Section 4.1 for more details.

Based on fits to the T2K data, we find the following tuned parameter values, with recommended uncertainties to be used in MicroBooNE analyses:

- MaCCQE = 1.18 ± 0.12
- CCQE RPA = 0.4 ± 0.4
- CCMEC Normalization = 1.26 ± 0.7
- CCMEC Cross-section Shape = $0.22^{+0.78}_{-0.22}$ (where the uncertainty is inflated to cover the full theoretical uncertainty between the two models because we do not expect this fit to be a reliable way to choose a MEC shape model).

Because the effect of increasing MaCCQE is broadly to increase the CCQE cross section normalization (with some additional changes in shape), we find fairly significant (∼50%) correlations between MaCCQE and the CCMEC Normalization parameter. We also see a roughly 35-40% correlation between MaCCQE and the CCQE RPA parameter (which, among other things, also affects the CCQE normalization). Our current uncertainty estimations do not consider correlations between these parameters; this is something that can be addressed in the future.

Unfortunately, after the fits were completed a bug was found in the CCMEC Cross-section Shape parameter, in which it was not behaving as a shape-only parameter but also changing the normalization of CCMEC events. The impact of the bug is to increase the normalization of CCMEC events as the parameter increases from 0 towards 1, with a larger normalization increase at lower energies. There was also a numerical integration problem causing CCMEC events with energies below 400 MeV to sometimes receive weights of 0. Because of this, we consider this tune preliminary and plan to update it once the bug has been fixed. We also recommend that analyses do not include the uncertainty on the CCMEC Cross-section Shape parameter until the bug is resolved. As a closure test, the fit to T2K data was repeated without the CCMEC Cross-section Shape parameter and very similar tuned values of the other parameters (MaCCQE, CCQE RPA, and CCMEC Normalization) were found: in all cases, consistent with the values given above within the quoted uncertainties. This gives confidence that, although this fit result is preliminary, the results are likely to be similar after the bug in CCMEC Cross-section Shape is fixed.

3.3.1 Preliminary comparisons to data

The figures in this section show some comparisons of this preliminary tune to published cross-section data from various neutrino experiments. The predictions from GENIE v2.12.2 and the nominal GENIE v3.0.6 G18_10a_02_11a are also overlaid for direct comparison. A small subset of comparisons to data from measurements in MicroBooNE, MiniBooNE, T2K, and MINERvA are shown in this section; after the tune is finalized and no longer preliminary, a more comprehensive set of comparisons to external data will be produced.

Figure 3 shows a comparison to the T2K CC0π analysis 1 data (i.e. the data to which the fit was performed). By design (since the fit was to this data set), the preliminary tuned prediction is in much better agreement with the data by eye, and is reflected in the χ^2. This figure shows the χ^2 calculated using diagonal terms of the covariance matrix only, in keeping with the χ^2 used in the fits.

Figure 4 shows the same data and predictions: this time the χ^2 are calculated using the full covariance matrix. This is not equivalent to the χ^2 used in the fits, where only diagonal elements in the bin-error covariance matrix were considered. We see that the χ^2 calculated in this way is smaller for the nominal GENIE v3 prediction (χ^2/nbins = 144/67) than the preliminary tune (χ^2/nbins = 215/67). Since the nominal GENIE v3 prediction has a lower normalization than the preliminary tune, this is consistent with the observation in section 3.2 that fitting with the full covariance matrix resulted in a significant and unphysical reduction of the cross section across all bins.

Figures 5 and 6 show comparisons to the published MicroBooNE CC-inclusive cross section measurement [3]. As seen with the T2K data in Figures 2, 3 and 4, the measurement is a double-differential cross section as a function of muon momentum (p_μ) and angle ($\cos\theta_\mu$). This is projected in Figures 5 and 6 onto a 1D histogram as a function of bin number, where the bin number loops over muon momentum in slices of fixed muon angle. We show backward-angle data in lower bins and forward-angle data in higher-numbered bins. Comparing to MicroBooNE data is, of course, particularly interesting, since it is the only data we have on argon. Figure 6 shows the preliminary tuned prediction with an uncertainty band corresponding to the four fit parameters varied according to the 1σ uncertainties recommended in Section 3.3. This shows that we should expect to see agreement with our data within the assigned uncertainties.

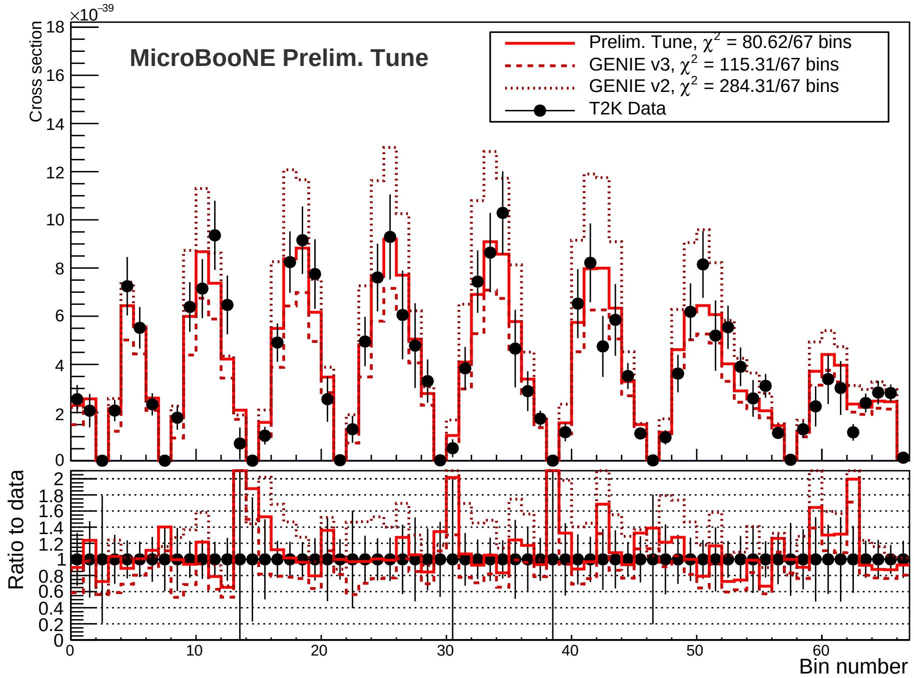


Figure 3: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit results to the T2K CC0π analysis 1 data. Note that the χ^2 shown in the plot are calculated using **only diagonal elements of the covariance matrix** (i.e. the χ^2 shown here are the same as the χ^2 used to determine good fit to the data).

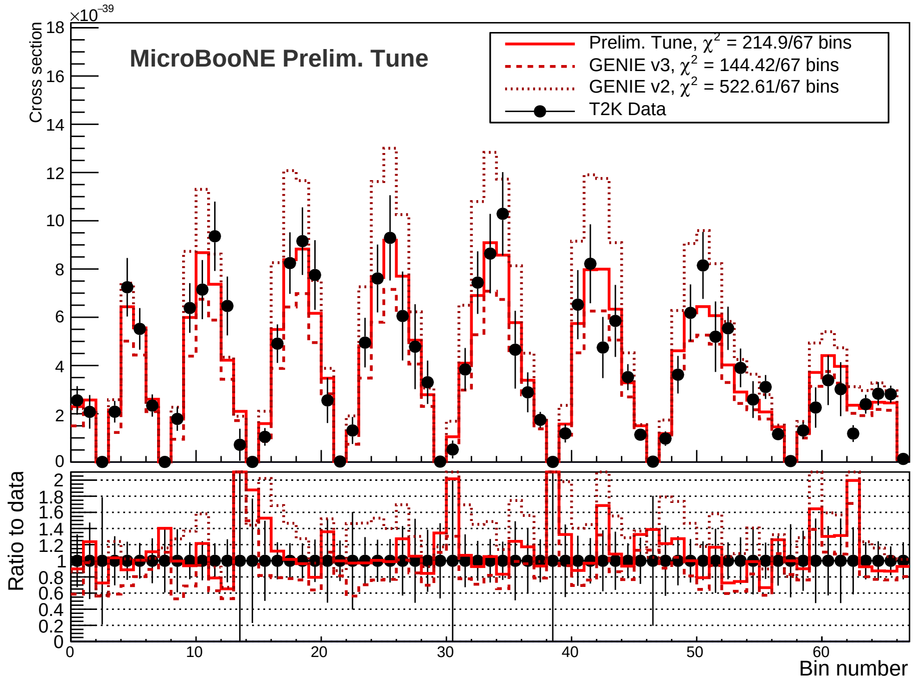


Figure 4: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit results to the T2K CC0π analysis 1 data. Note that the χ^2 shown in the plot are calculated using the **full analysis covariance matrix**. The χ^2 shown here do not come from the fits and aren't compatible with those from the fits; for the fits, only diagonal elements in the bin-error covariance matrix were considered. Otherwise, the predictions and data shown here are identical to Figure 3.

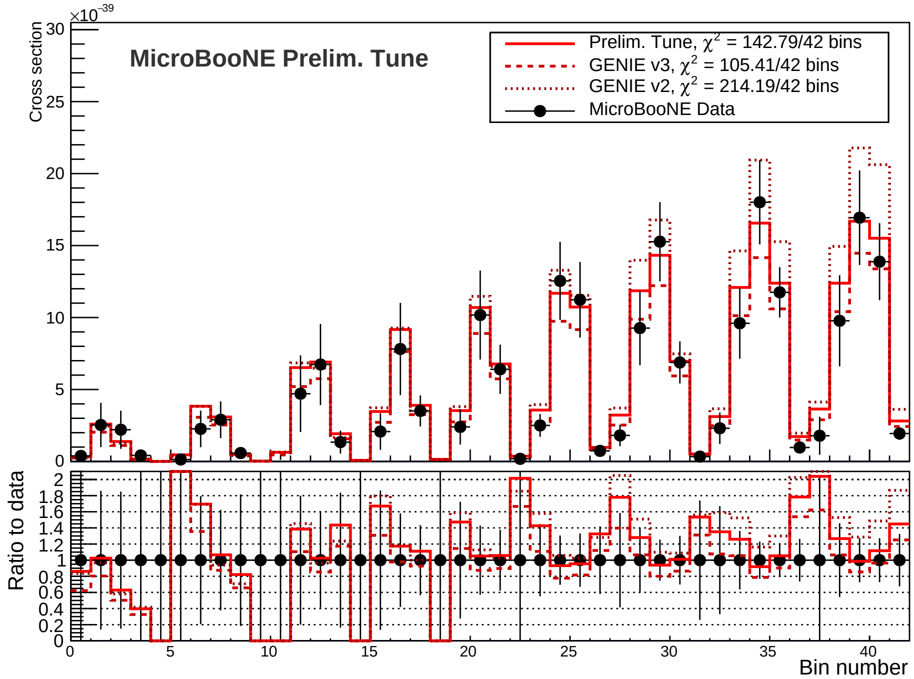


Figure 5: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to the MicroBooNE CC-inclusive cross-section measurement [3].

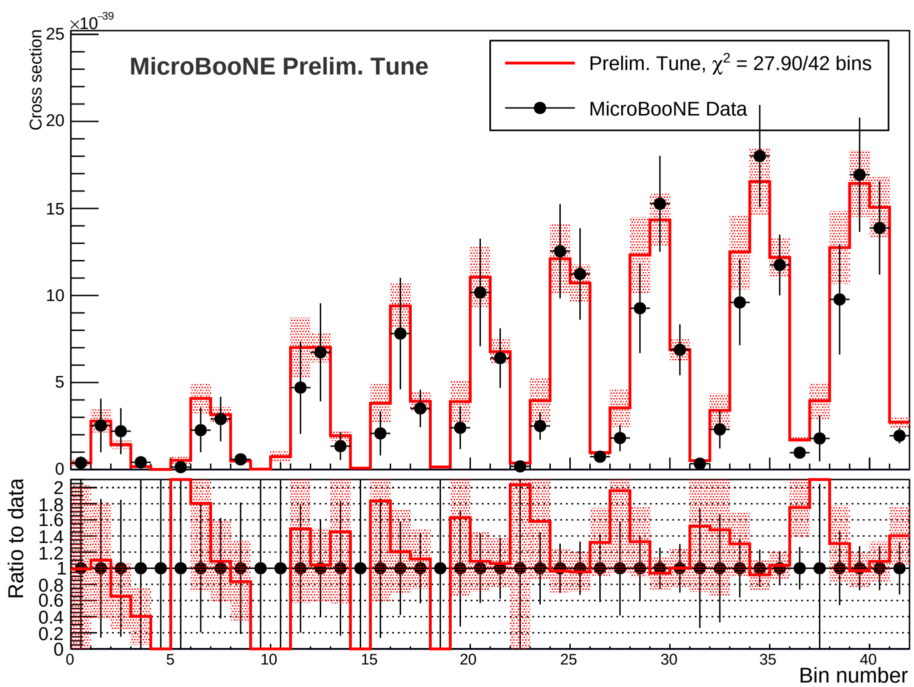
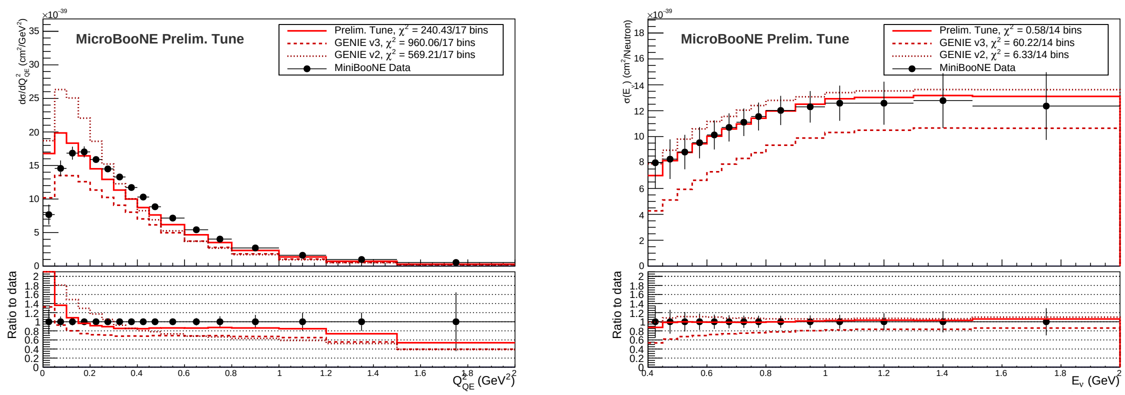


Figure 6: Comparison of the preliminary fit result with uncertainties on the four fit parameters (as outlined in Section 3.3) to the MicroBooNE CC-inclusive cross-section measurement [3]. When including both uncertainties on the data and the uncertainties on our model prediction, we see good agreement: χ^2/nbins = 27.90/42.

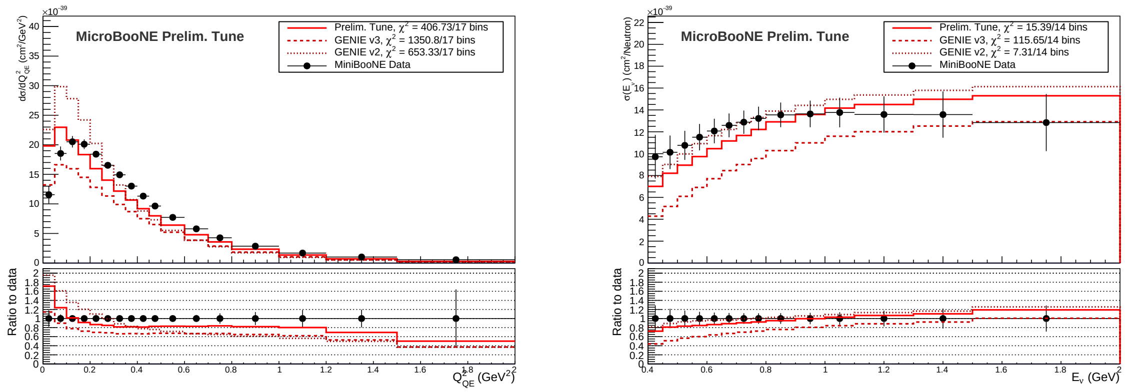
CC0π measurements Since we have tuned only CCQE and CCMEC parameters, we expect the impact of this tune to be most visible on measurements of CCQE-like or CC0π processes. Figures 7 and 8 show comparisons of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to MiniBooNE CCQE and CCQE-like data [16]. In both cases the same measured data are used: the difference is how the signal is defined. The MiniBooNE "CCQE" signal definition includes true CCQE and CCMEC interactions only, whereas the "CCQE-like" data set considers any interaction in which one muon, any number of nucleons, and no other particles are produced to be signal (often called "CC0π" in current experiments). In the "CCQE" data we see significantly better agreement between the preliminary tuned prediction and the data than for either GENIE v2.12.2 or GENIE v3.0.6 G18_10a_02_11a. In the CCQE-like case the agreement is somewhat less good, but the preliminary tuned prediction still shows a vast improvement over nominal GENIE v3.0.6 G18_10a_02_11a. We note that the data here include systematic errors, which are largely correlated, but the MiniBooNE data releases for this measurement do not include a covariance matrix so there is no way to properly account for correlations in the χ^2 calculation. The result of this is some very small χ^2 values, as shown in the figures (particularly Figure 7b).

We see a similar trend in the T2K CC0π data shown in Figure 9. The figure shows analysis 2 from the same T2K paper that we fit to [4] (so contains largely the same data as analysis 1, to which we fit), but instead of a 2D cross section, two 1D cross sections are shown, as a function of muon momentum and angle. This makes it a little easier to understand the plot by eye.



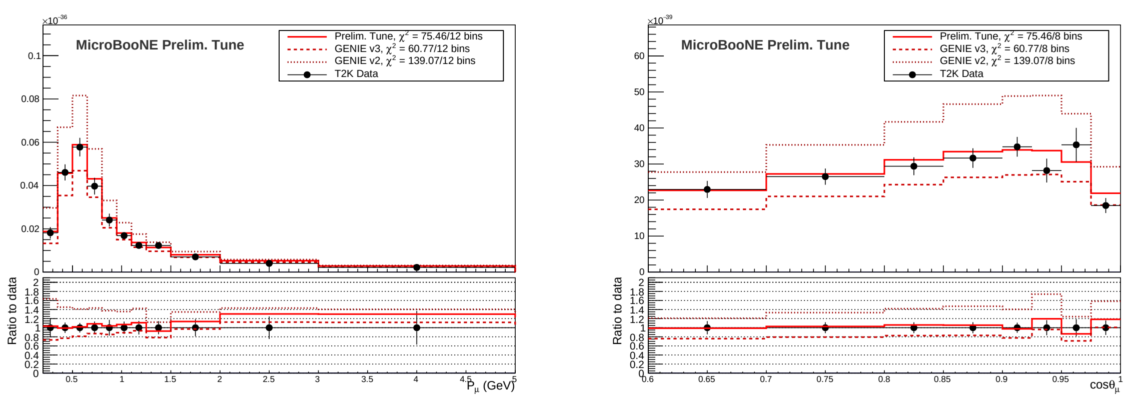
(a) Q^2 (b) E_ν

Figure 7: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to the MiniBooNE CCQE data [16]. The CCQE signal definition includes true CCQE and CCMEC, but not pion production and subsequent absorption in the nucleus. Note that no covariance matrix is available for this data set, so the χ^2 shown in the plot are calculated without bin-to-bin correlations.



(a) Q^2 (b) E_ν

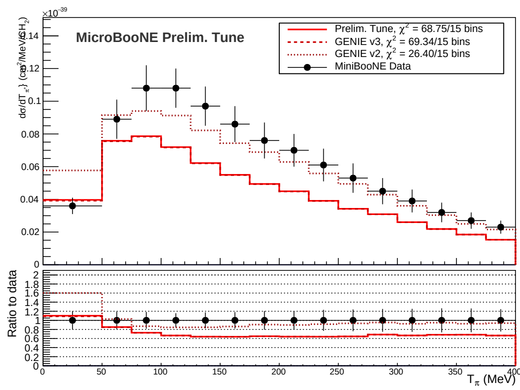
Figure 8: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to the MiniBooNE CCQE-like data [16]. The CCQE-like signal definition is often now called CC0π: it includes events in which one muon, any number of nucleons, and no other final state particles exit the nucleus. The main components are true CCQE, CCMEC, and RES/DIS with pion absorption in the nucleus. Note that no covariance matrix is available for this data set, so the χ^2 shown in the plot are calculated without bin-to-bin correlations.



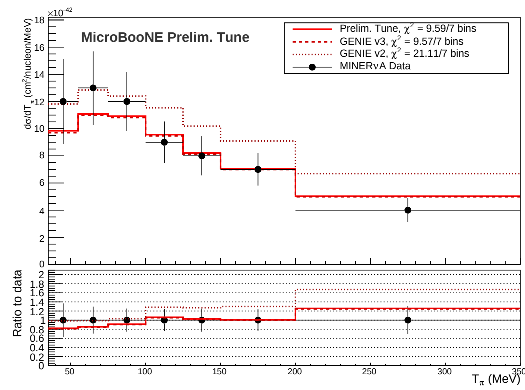
(a) Muon momentum (b) Muon cosθ

Figure 9: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to 1D cross sections from the T2K CC0π: analysis 2 data [4].

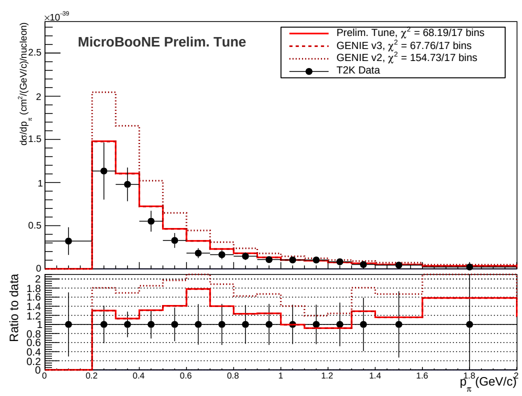
CC1π^+ measurements Figure 10 shows the comparison of our models to measured CC1π^+ data from MiniBooNE [26], MINERvA [10], and T2K [9]. We see very close agreement between the GENIE v3.0.6 G18_10a_02_11a "nominal" and "preliminary tuned" predictions – we expect this is driven by the fact that we did not tune the pion production models. While we do expect differences due to CCQE and CCMEC background interactions being selected (as well as signal interactions coming from a CCQE/CCMEC interaction in which a pion is produced via FSI), the fact that we do not see large differences indicates both that the selections are relatively pure in RES/DIS interactions and the effect of the tune in the phase-space regions selected by these analyses is small. However, it is still interesting to note the differences between GENIE v2.12.2 and GENIE v3.0.6 G18_10a_02_11a. The primary cause of the normalization shift from GENIE v2.12.2 to GENIE v3.0.6 G18_10a_02_11a is an improved fit to the neutrino deuterium pion production data. MiniBooNE shows a strong preference for GENIE v2.12.2, whereas MINERvA favours GENIE v3.0.6 G18_10a_02_11a. This is a long-standing and well-known problem, often called the "pion puzzle". Newly published data from T2K also favours GENIE v3.0.6 G18_10a_02_11a.



(a) MiniBooNE: T$_\pi$ [26]



(b) MINERvA: T$_\pi$ [10]

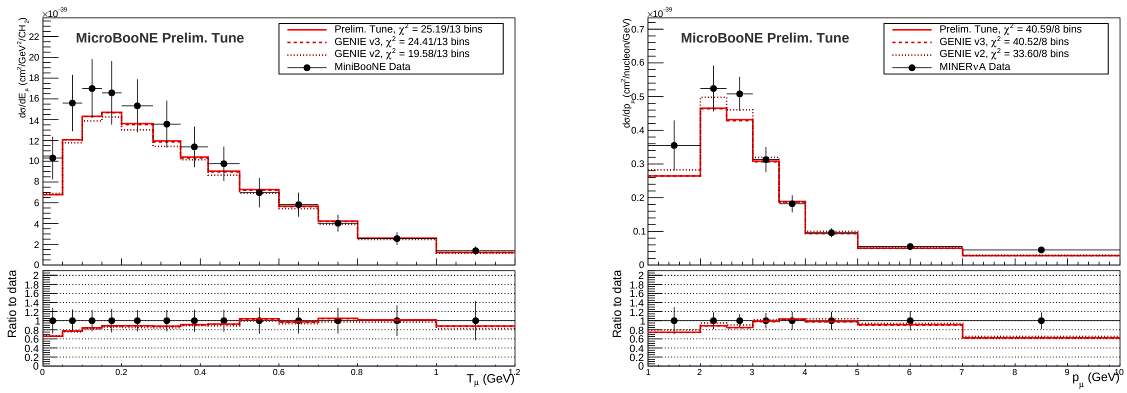


(c) T2K: p$_\pi$ [9]

Figure 10: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to CCπ^+ cross sections as a function of charged pion momentum/kinetic energy as measured in MiniBooNE, MINERvA, and T2K.

π^0 **measurements** Figure 11 shows the 1D CCπ^0 cross-sections as a function of muon momentum/kinetic energy as measured in MiniBooNE [27] and MINERvA [8]. In both cases we see good agreement between the "nominal" and "preliminary tuned" GENIE v3.0.6 G18_10a_02_11a predictions (likely for the same reason we saw good agreement in the CC1π^+ predictions above), and we see that the χ^2 is slightly lower for GENIE v2.12.2 than v3.0.6 G18_10a_02_11a. However, the difference in χ^2 is small, and in general the predictions are in fairly good agreement.

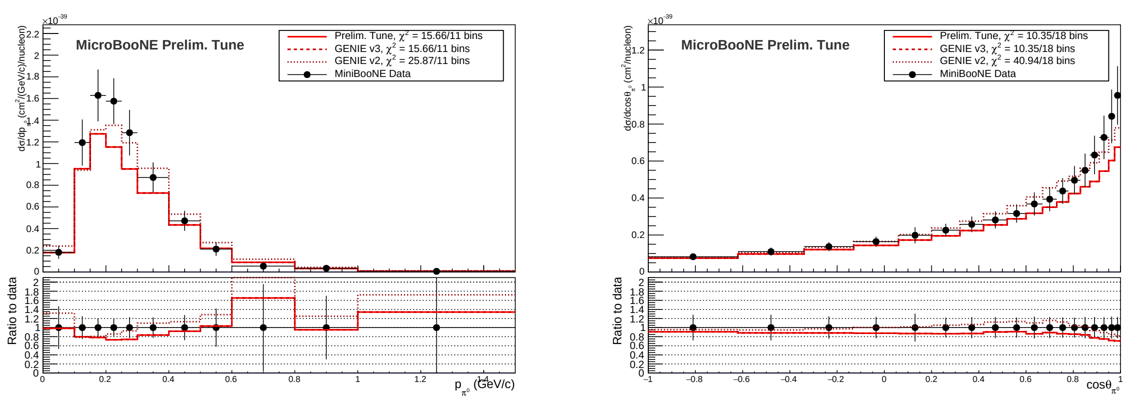
Figure 12 shows comparisons with the MiniBooNE measured NCπ^0 cross sections [28]. Although by eye the GENIE v2.12.2 normalization may seem to fit the data better, the χ^2 is lower for v3.0.6 G18_10a_02_11a, indicating a better agreement when bin-to-bin correlations are taken into account. Again, as expected, we see no difference between "nominal" and "preliminary tuned" v3.0.6 G18_10a_02_11a.



(a) MiniBooNE: T_μ [27]

(b) MINERvA: p_μ [8]

Figure 11: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to 1D CCπ^0 cross sections as a function of muon momentum/kinetic energy from MiniBooNE and MINERvA.



(a) p_{π^0}

(b) $\cos\theta_{\pi^0}$

Figure 12: Comparison of the GENIE v2.12.2 prediction, GENIE v3.0.6 G18_10a_02_11a prediction, and the preliminary fit result to 1D NCπ^0 cross sections measured in MiniBooNE [28].

4 Model Uncertainties

This section describes the recommended parameter values and uncertainties for all parameters in the GENIE v3.0.6 models used by MicroBooNE analyses. The recommendations are determined in a few different ways:

1. For the CCQE and CCMEC model parameters that were fit to T2K data, we take the uncertainties estimated through the fitting procedure, as described in Section 3.3
2. The GENIE collaboration has already performed tuning to various data sets to estimate parameter values and uncertainties, so for parameters where we have no strong indications from internal or external data that the values or uncertainties should be changed, we use the default values and uncertainties from GENIE v3.0.6 G18_10a_02_11a.
3. For model uncertainties that are not included in the default GENIE uncertainties, we devise our own parameters, as described in Section 4.1. Where the uncertainty on these parameters is not based on data, we are conservative (e.g. for parameters that interpolate between two models that are equally valid according to comparisons to world data, we choose the full difference between the two models as the uncertainty).

The uncertainties recommended in this document are still under review, and in some cases further comparisons to external and internal (MicroBooNE) data are being performed to build confidence in the values chosen. Therefore, future analyses may update the uncertainties slightly. However, we believe that the uncertainties presented here are close to complete, as discussed in Section 5.

Most of the uncertainties in this document are evaluated in MicroBooNE analyses using a "multisim" method, in which almost all of the various model parameters are varied randomly and simultaneously according to Gaussian distributions, with 1σ uncertainties defined in Section 4.2. Varying parameters simultaneously allows analyses to take into account the effects of simultaneous shifts between these parameters assuming that the uncertainties in the parameters are uncorrelated.

The multisim method is not feasible in some cases, for example where it is not possible to reweight to different parameter values and instead the simulation must be regenerated; or for parameters in which we don't recommend a true 1σ uncertainty, but instead recommend taking the full range of a parameter as the uncertainty. In these cases, uncertainties are evaluated by a small number of variations in the parameter value, where only this parameter is varied: this is called the "unisim" method.

4.1 New Reweighting Parameters

There are some uncertainties we would like to account for that are not currently included in the reweight package provided with GENIE v3.0.6. For example, it does not provide any official reweighting tools that are compatible with the Valencia MEC model [18, 19, 20]. However, MicroBooNE has internally developed a patched version of the GENIE Reweight product which adds a nearly comprehensive set of tools for manipulating the Valencia MEC model, as well as other required parameters. These are described below.

- **CCQE RPA**: This parameter interpolates between the default Valencia RPA prediction implemented in GENIE v3.0.6 G18_10a_02_11a (dial value = 0) and RPA entirely turned off (dial value = 1). This approach accounts for the full radial, kinematic, and energy dependence of the RPA effect on an event-by-event basis. Based on the fits to T2K data presented in section 3, we recommend a 100% uncertainty on the central value of 0.4, to ensure that the Valencia RPA prediction is included within the 1σ uncertainty.
- **CCMEC Normalization**: This parameter scales the total CCMEC cross section by a constant factor. There is strong evidence from experiments such as T2K, MINERvA, NOvA, and MiniBooNE that MEC events exist, and MINERvA sees evidence for the strength of MEC interactions being larger than is currently in GENIE. Because of this, we think it is not possible for the CCMEC normalization to be 0, but we expect a larger uncertainty for positive variations to larger values. Therefore, in the absence of evidence from T2K fits we would propose $+1\sigma/-1\sigma$ variations of +1/-0.5. This is consistent with the uncertainty extracted from the fits to T2K data presented in Section 3.3, where we recommend a 1-sigma uncertainty of 0.7 (or $\pm$56%) around a central value of 1.26.
- **CCMEC Decay Angle**: GENIE uses a method that has been called the "nucleon cluster model" [29] to predict hadronic final states for MEC events. In this approach, the momentum transfer is imparted to a pair of nucleons that are treated as a single object. The pair is decayed isotropically in its rest frame into two on-shell final-state nucleons. Although theory predictions for a more realistic angular distribution are in principle

calculable, an exact treatment is complicated, and nothing better than an isotropic distribution is available in an event generator. In an attempt to account for the uncertainty associated with this approximation, this parameter allows us to vary angular distribution of the nucleon cluster decays between two extremes. A value of 0 corresponds to the GENIE default behavior (isotropic) while a value of 1 corresponds to a $\cos^2\theta$ distribution. A linear interpolation between the two distributions is performed for intermediate values on the interval $[0, 1]$, and parameter values outside of this range are invalid. The choice of the alternate distribution is ad hoc rather than theoretically motivated. It is intended to be a significant departure from the default isotropic model. To allow us to quantify how sensitive an analysis is to the true angular distribution in CC MEC events, we recommend taking the uncertainty as the full difference between the two variations.

- **CC MEC pn Fraction**: This parameter varies the fraction of initial nucleon pairs in MEC interactions that are pn (i.e. one proton and one neutron). In electron scattering, it is known that pn pairs dominate MEC interactions, accounting for roughly 80% of events. However, it is not clear if that information can be directly applied to neutrino scattering. The Nieves MEC calculation predicts that the pn contribution to the total cross section will vary as a function of the energy and momentum transfer (q^0, $|\mathbf{q}|$). We recommend taking this prediction as our central value with a symmetric 20% uncertainty. Values of the varied pn fraction beyond the interval [0,1] are not allowed by the GENIE reweight calculator and are corrected as needed. This conserves the total MEC cross section in the presence of these variations.

- **CC MEC Delta-like Fraction**: The Nieves MEC calculation includes contributions to the amplitude from two kinds of Feynman diagrams. Some of these involve an internal Δ resonance while others do not. This knob varies the relative contribution of the Δ diagrams to the total cross section. Like the CC MEC pn Fraction parameter, this is done for fixed lepton kinematics, and the fractional variation is restricted to the interval [0,1]. In the absence of a competing model that makes these distinctions, we recommend a 30% uncertainty on this quantity.

- **CC MEC Cross-section Shape**: This parameter varies the shape of the CCMEC differential cross section between our default Nieves MEC model (parameter = 0) and the alternative GENIE empirical MEC model (parameter = 1). Intermediate values on [0,1] can be used to linearly interpolate between these two extremes, and parameter values outside of this range are invalid. Although the Nieves and empirical MEC models differ in their normalization, this parameter was intended to conserve the total MEC cross section and simply reshapes the lepton kinematic distribution in (q^0, $|\mathbf{q}|$) space. Unfortunately, a bug has been found in which the parameter also changes the normalization. Because of this, we consider the tune including this parameter to be preliminary and plan to update it with a bug-free parameter at a later stage. We also recommend that analyses do not include the uncertainty on the CC MEC Cross-section Shape parameter until it has been fixed.

4.2 Parameter Values and Uncertainties

The tables below summarize the parameters and uncertainties considered in our cross-section model.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
MaCCQE	CCQE axial mass (replaces combination of NormCCQE and MaCCQEshape)	1.18 GeV	0.1	-0.1
CCQE RPA	Strength of the RPA correction	0.4	1.0	-1.0
AxFFCCQEshape	Parameterization of the nucleon axial form factor	0 (dipole)	1 (z-expansion)	N/A
VecFFCCQEshape	Parameterization of the nucleon vector form factors	0 (BBA07)	1 (dipole)	N/A
Coulomb_CCQE	Value of Coulomb potential used in corrections for CCQE	0 (nominal)	0.3	-0.3

Table 1: CCQE model parameters with recommended central values and $\pm 1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
CC MEC Normalization	Energy-independent normalization for CCMEC	1.26	+0.56	-0.56
CC MEC Decay Angle	Changes angular distribution of nucleon cluster	0 for isotropic in rest frame (default)	1 for $\cos^2\theta$ in rest frame	N/A
CC MEC pn Fraction	Varies fraction of initial nucleon pairs that are pn	0 for Valencia prediction (default)	+0.2	-0.2
CC MEC Delta-like Fraction	Varies relative contribution of Δ diagrams to total MEC cross section	0 for Valencia prediction (default)	+0.3	-0.3
CC MEC Cross-section Shape	Changes shape of differential cross section	0.22	-	-

Table 2: CC MEC model parameters with recommended central values and $\pm1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
MaCCRES	CCRES axial mass (use with MvCCRES to replace combination of NormCCRES, MaCCRESshape, and MvCCRESshape)	1.120 GeV	0.2	-0.2
MvCCRES	CCRES vector mass (use with MaCCRES to replace combination of NormCCRES, MaCCRESshape, and MvCCRESshape)	0.840 GeV	0.1	-0.1
MaNCRES	NCRES axial mass (replaces combination of NormNCRES, MaNCRESshape, and MvNCRESshape)	1.120 GeV	0.2	-0.2
MvNCRES	NCRES vector mass (replaces combination of NormNCRES, MaNCRESshape, and MvNCRESshape)	0.840 GeV	0.1	-0.1
RDecBR1gamma	Normalization for radiative decays of baryon resonances (i.e., those involving photon emission)	Nominal branching ratio	0.5	-0.5
RDecBR1eta	Normalization for decays of baryon resonances involving η emission	Nominal branching ratio	0.5	-0.5
Theta_Delta2Npi	Interpolates angular distribution for $\Delta \rightarrow N + \pi$ between Rein-Sehgal model (0) and isotropic (1)	0 (for default Rein-Sehgal prediction)	1 (for isotropic distribution)	N/A
ThetaDelta2NRad	Interpolates angular distribution for $\Delta \rightarrow N + \gamma$ between isotropic (0) and $\propto \cos^2\theta$ (1)	0 (isotropic)	1 ($\propto \cos^2\theta$)	N/A

Table 3: Resonance model parameters with recommended central values and $\pm 1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
NormCCCOH	Scaling factor for CC COH π production	0 (nominal)	1	-1
NonRESBGvpCC1pi	Non-resonant background normalization for νp CC1π	0.007713	0.5	-0.5
NonRESBGvpCC2pi	Non-resonant background normalization for νp CC2π	0.787999	0.5	-0.5
NonRESBGvnCC1pi	Non-resonant background normalization for νn CC1π	0.127858	0.5	-0.5
NonRESBGvnCC2pi	Non-resonant background normalization for νn CC2π	2.11523	0.5	-0.5
NonRESBGvbarpCC1pi	Non-resonant background normalization for $\bar{\nu}$p CC1π	0.127858	0.5	-0.5
NonRESBGvbarpCC2pi	Non-resonant background normalization for $\bar{\nu}$p CC2π	2.11523	0.5	-0.5
NonRESBGvbarnCC1pi	Non-resonant background normalization for $\bar{\nu}$n CC1π	0.007713	0.5	-0.5
NonRESBGvbarnCC2pi	Non-resonant background normalization for $\bar{\nu}$n CC2π	0.787999	0.5	-0.5
AhtBY	A_HT higher-twist parameter in the Bodek-Yang model scaling variable xi_w	0.538	0.25	-0.25
BhtBY	BHT higher-twist parameter in the Bodek-Yang model scaling variable xi_w	0.305	0.25	-0.25
CV1uBY	CV1u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.291	0.3	-0.3
CV2uBY	CV2u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.189	0.4	-0.4
AGKYxF1pi	Hadronization parameter, applicable to true DIS interactions only	-0.385	0.2	-0.2
AGKYpT1pi	Hadronization parameter, applicable to true DIS interactions only	1/6.625	0.03	-0.03

Table 4: CC non-resonant, transition, DIS, and coherent scattering model parameters with recommended central values and $\pm 1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
NormNCMEC	Energy-independent normalization for NCMEC	1	1.0	-1.0
MaNCEL	Axial mass for NCEL	0.961242 GeV	0.25	-0.25
EtaNCEL	Empirical parameter used to account for strange quark contribution to NCEL form factor	0.12	0.3	-0.3
NonRESBGvpNC1pi	Non-resonant background normalization for νp NC1π	0.1	0.5	-0.5
NonRESBGvpNC2pi	Non-resonant background normalization for νp NC2π	1	0.5	-0.5
NonRESBGvnNC1pi	Non-resonant background normalization for νn NC1π	0.3	0.5	-0.5
NonRESBGvnNC2pi	Non-resonant background normalization for νn NC2π	1	0.5	-0.5
NonRESBGvbarpNC1pi	Non-resonant background normalization for $\bar{\nu}$p NC1π	0.3	0.5	-0.5
NonRESBGvbarpNC2pi	Non-resonant background normalization for $\bar{\nu}$p NC2π	1	0.5	-0.5
NonRESBGvbarnNC1pi	Non-resonant background normalization for $\bar{\nu}$n NC1π	0.1	0.5	-0.5
NonRESBGvbarnNC2pi	Non-resonant background normalization for $\bar{\nu}$n NC2π	1	0.5	-0.5
NormNCCOH	Scaling factor for NC COH π production	0 (nominal)	1	-1

Table 5: Neutral current model parameters with recommended central values and $\pm 1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

Parameter	Meaning	Recommended central value	Recommended $+1\sigma$	Recommended -1σ
MFP_pi	π mean free path (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.2	0.2
MFP_N	Nucleon mean free path (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.2	0.2
FrCEx_pi	Fractional cross section for π charge exchange (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.5	0.5
FrInel_pi	Fractional cross section for π inelastic scattering (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.4	0.4
FrAbs_pi	Fractional cross section for π absorption (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.3	0.3
FrPiProd_pi	Fractional cross section for π-induced π production (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.2	0.2
FrCEx_N	Fractional cross section for nucleon charge exchange (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.5	0.5
FrInel_N	Fractional cross section for nucleon inelastic scattering (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.4	0.4
FrAbs_N	Fractional cross section for nucleon absorption (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.2	0.2
FrPiProd_N	Fractional cross section for nucleon-induced π production (nominal value corresponds to hA2018 prediction)	0 (for default hA model)	0.2	0.2

Table 6: FSI model parameters with recommended central values and $\pm 1\sigma$ uncertainties. Note that all uncertainties are fractional unless otherwise stated.

5 Comparison to other models

While the performance of the preliminary "MicroBooNE tune" described herein is best assessed through confrontation with data, understanding the degree to which the tune differs from competing neutrino interaction models may also be useful. This is particularly true for low-hundreds-of-MeV neutrino energies. To date, nearly all accelerator neutrino cross section datasets provide information on flux-averaged quantities using a broad range of neutrino energies.[1] Despite their usefulness for constraining neutrino interaction models in general, the available measurements thus have limited sensitivity to mismodeling specifically at low energies. Confidence that the cross section model adopted for use in MicroBooNE's LEE search is fit for purpose must therefore primarily come from comparisons of the reconstructed neutrino energy distribution obtained in data and simulation by each LEE analysis.

In this document, we provide a supplemental study aimed at gauging plausibility. Assuming that the disagreement seen between a set of suitably-chosen cross section models is reflective of the true theoretical uncertainty, the degree to which our recommended error band covers the set provides a tentative metric (pending confirmation with data) for the adequacy of our approach.

Figures 13 and 14 show the results of such a coverage study for energy-dependent CC inclusive total cross sections for ν_μ-^{40}Ar and ν_e-^{40}Ar scattering, respectively. The solid black histograms on each plot show the cross section predicted by the preliminary "MicroBooNE tune" (hereafter denoted by *GENIEv3Tuned*) described in this document. To produce these predictions, which are averaged over each energy bin, two million CC inclusive GENIE events per flavor were generated using a uniform flux from threshold up to 1 GeV. The gray shaded regions show the one-sigma uncertainty on the *GENIEv3Tuned* model obtained according to the recommendations given in Sec. 4.

In Figures 13a and 14a, the full neutrino energy range (0.1 to 1 GeV) studied is shown. Figures 13b and 14b limit the maximum neutrino energy to 0.3 GeV. Several alternative models are compared to *GENIEv3Tuned* on all of the plots. They are labeled as follows:

Untuned GENIE v3 The cross section as predicted by GENIE v3.0.6 `G18_10a_02_11a`, without any tuning by MicroBooNE

Low-BE Identical to Untuned GENIE v3, except that the constant nucleon binding energy used by the local Fermi gas model was lowered from 29 MeV to 10 MeV.

GENIE v2 The default model set for GENIE v2.12.2

GENIE SuSAv2 A new model set under development within GENIE and expected to be included as part of the upcoming GENIE v3.2 release. CCQE and CCMEC cross sections are calculated according to the SuSAv2 (SuperScaling Approach version 2) model [31, 32]. The configuration is otherwise nearly identical to GENIE v3.0.6 `G18_10b_00_000` (and similar to Untuned GENIE v3).

NuWro A calculation performed using version 19.02.1 of the NuWro [14] neutrino event generator. Default settings were used for most model parameters, with the only important changes being the following:

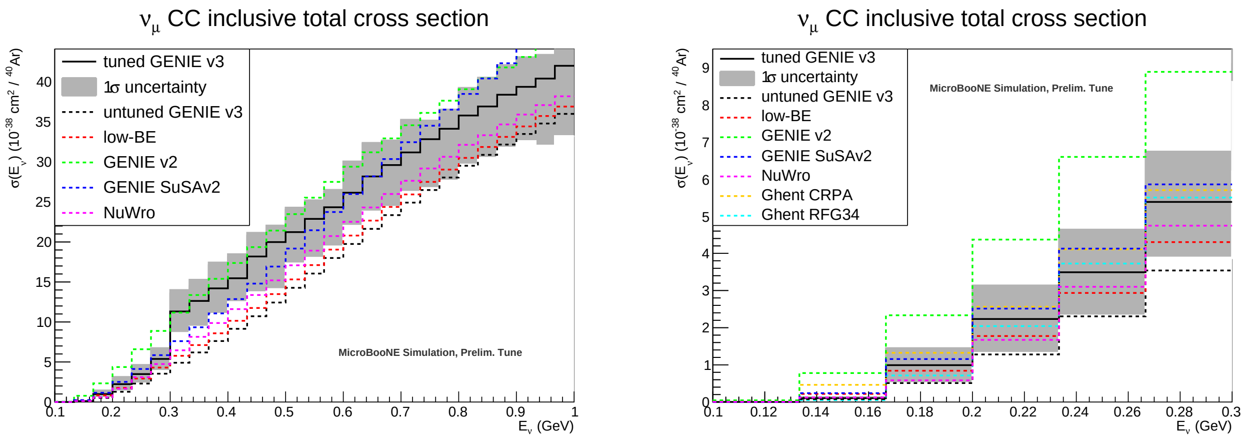
```
qel_cc_axial_mass = 1000
qel_rpa = 1
pion_axial_mass = 1.00
mec_kind = 3
```

In order of appearance, these lines in the NuWro configuration file set the CCQE axial mass to 1 GeV, enable RPA corrections in the CCQE cross section (distinct from the RPA approach used in the Nieves CCQE model), set the axial mass used in RES cross section calculations to 1 GeV, and enable use of the Valencia model for CCMEC interactions.

Two additional models are included in the right-hand plots restricted to low neutrino energies:

Ghent CRPA A Continuum Random Phase Approximation (CRPA) calculation [33] performed by N. Jachowicz (Ghent University), V. Pandey (U. Florida), and collaborators. This model [34] includes nuclear structure details (e.g., giant resonance excitations) which are potentially important at low energy and not included in the other models studied here.

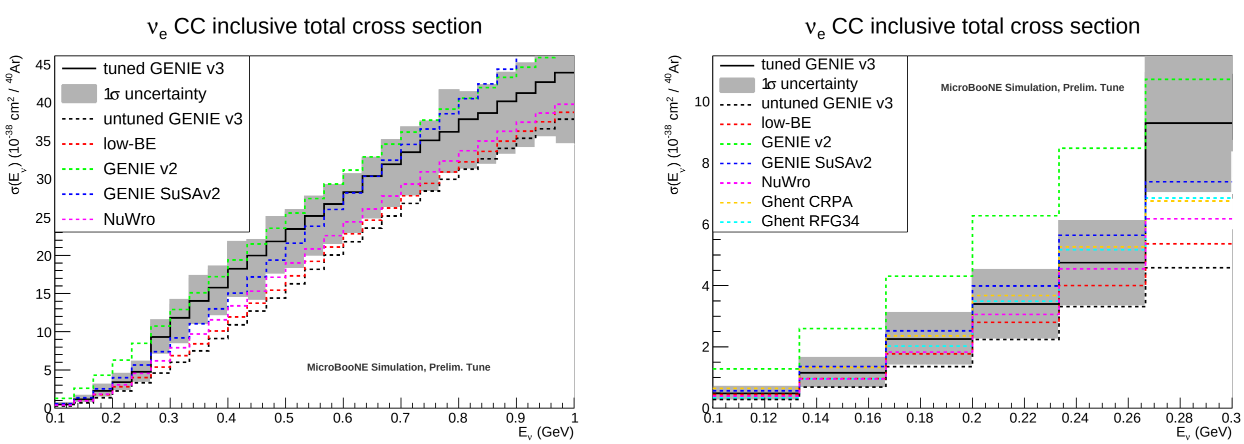
Ghent RFG34 A second calculation from the same group. In this case, a much simpler Relativistic Fermi Gas (RFG) description of the nucleus is adopted while preserving other aspects of the theory treatment. A constant nucleon binding energy of 34 MeV is assumed for the RFG calculation.



(a) $0.1 < \mathrm{E}_\nu < 1$ GeV

(b) $0.1 < \mathrm{E}_\nu < 0.3$ GeV

Figure 13: Comparison of the *GENIEv3Tuned* central value model and uncertainties to competing models. The ν_μ-^{40}Ar CC inclusive cross section is shown as a function of neutrino energy.



(a) $0.1 < \mathrm{E}_\nu < 1$ GeV

(b) $0.1 < \mathrm{E}_\nu < 0.3$ GeV

Figure 14: Comparison of the *GENIEv3Tuned* central value model and uncertainties to competing models. The ν_e-^{40}Ar CC inclusive cross section is shown as a function of neutrino energy.

Below 0.3 GeV, coverage of the alternative models other than GENIE v2 by the *GENIEv3Tuned* uncertainty band is generally good. The two exceptions are below 0.165 GeV for ν_μ (which is likely below the detection thresholds for many, if not all, analyses) and the ν_e energy bin just below 0.3 GeV. The latter discrepancy, as well as the poor coverage seen from roughly 0.3 to 0.6 GeV, is partially attributable to the bug found in the code used to vary the CC MEC Cross-section Shape parameter (see Sec. 3.3). In this energy region, the bug leads to an upward bias in the CCMEC cross section, leading to the large bin-to-bin change seen in the vicinity of 0.3 GeV for the *GENIEv3Tuned* cross section for both ν_μ and ν_e. Resolution of this problem is expected to bring the *GENIEv3Tuned* model in closer agreement with the majority of the competing calculations in the affected energy region.

[1] An exception is the measurement by MiniBooNE of monoenergetic ν_μ from charged kaon decay at rest [30].

6 Conclusions

The measurements being performed by the MicroBooNE collaboration require a baseline that reflects an accurate rendering of the existing neutrino cross section data with realistic uncertainties. The GENIE collaboration provides all this information in an organized way. However, the theoretical understanding of these cross sections is in flux. Since GENIE v3 has a much better agreement with existing data than GENIE v2, it is used as the base simulation for MicroBooNE analyses, but this simulation was found to underpredict the cross section for CC0π interactions. This document presents a tuning of the CCQE and CCMEC models to improve agreement with data; to avoid problems in future fits using LEE data, only external data was considered for this tuning. We focus on Analysis 1 of the 2016 T2K CC0π data set [4], which has a neutrino energy range similar to MicroBooNE. Because of difficulties suspected to be associated with Peelle's Pertinent Puzzle, only the on-diagonal uncertainties from the published covariance matrix were used and bin-to-bin correlations between uncertainties were not considered.

The choice of parameters is always important in any tuning exercise. Since the major interactions in the MicroBooNE energy range ($\langle E_\nu \rangle \sim 700$ MeV) are QE and MEC, the magnitudes of these channels, RPA strength, and MEC shape were varied for an optimal fit. We call this a preliminary result because a bug in the fitting was recently found, but also because further optimization is possible. The result is a 30% improvement in the goodness-of-fit χ^2 between T2K data and simulation. The new fit result also has better agreement with MiniBooNE CC0π data [16] and MicroBooNE CC-inclusive data [3]. This is especially interesting because both MiniBooNE and T2K data sets were for a carbon target and MicroBooNE uses an argon target. Although this fit is preliminary, it has excellent agreement with existing data and is used for MicroBooNE analyses presented at Neutrino 2020.

This document also presents model uncertainties used for MicroBooNE analyses. For parameters included in the fit described above, an estimated uncertainty from the fit is used. Since the GENIE collaboration provides estimated uncertainties for GENIE parameters based on comparisons to world data, we use GENIE recommendations for uncertainties for parameters that aren't included in the fit. In the cases that GENIE recommendations are not given (i.e. for parameters that are not included in the GENIE reweighting package and were developed by MicroBooNE for this work), conservative uncertainty estimates are taken when uncertainties cannot be informed by data. Initial comparisons indicate that the preliminary tuned model is in agreement – within uncertainties – with other available models of neutrino interactions in MicroBooNE's energy range.

References

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