

# Neutrino-nucleus $CC0\pi$ cross-section tuning in GENIE v3

Júlia Tena-Vidal,<sup>1,\*</sup> Costas Andreopoulos,<sup>1,2</sup> Adi Ashkenazi,<sup>3</sup> Joshua Barrow,<sup>4,3</sup> Steven Dytman,<sup>5</sup> Hugh Gallagher,<sup>6</sup> Alfonso Andres Garcia Soto,<sup>7</sup> Steven Gardiner,<sup>8</sup> Matan Goldenberg,<sup>3</sup> Robert Hatcher,<sup>8</sup> Or Hen,<sup>4</sup> Timothy J. Hobbs,<sup>8,9</sup> Igor D. Kakorin,<sup>10</sup> Konstantin S. Kuzmin,<sup>10,11</sup> Anselmo Meregalia,<sup>12</sup> Vadim A. Naumov,<sup>10</sup> Afroditi Papadopoulou,<sup>4</sup> Gabriel Perdue,<sup>8</sup> Marco Roda,<sup>1</sup> Alon Sportes,<sup>3</sup> Noah Steinberg,<sup>8</sup> Vladyslav Syrotenko,<sup>6</sup> and Jeremy Wolcott<sup>6</sup>

(GENIE Collaboration)

<sup>1</sup>*University of Liverpool, Dept. of Physics, Liverpool L69 7ZE, UK<sup>†</sup>*

<sup>2</sup>*Science and Technology Facilities Council, Rutherford Appleton Laboratory, Particle Physics Dept., Oxfordshire OX11 0QX, UK*

<sup>3</sup>*Tel Aviv University, Tel Aviv 69978, Israel*

<sup>4</sup>*Massachusetts Institute of Technology, Dept. of Physics, Cambridge, MA 02139, USA*

<sup>5</sup>*University of Pittsburgh, Dept. of Physics and Astronomy, Pittsburgh PA 15260, USA*

<sup>6</sup>*Tufts University, Dept. of Physics and Astronomy, Medford MA 02155, USA*

<sup>7</sup>*Harvard University, Dept. of Physics, Cambridge, MA 02138, USA*

<sup>8</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

<sup>9</sup>*Department of Physics, Illinois Institute of Technology, Chicago, IL 60616, USA*

<sup>10</sup>*Joint Institute for Nuclear Research (JINR), Dubna, Moscow region, 141980, Russia*

<sup>11</sup>*Alikhanov Institute for Theoretical and Experimental Physics (ITEP) of NRC “Kurchatov Institute”, Moscow, 117218, Russia*

<sup>12</sup>*CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France*

(Dated: June 27, 2022)

This article summarizes the state of the art of  $\nu_\mu$  and  $\bar{\nu}_\mu$   $CC0\pi$  cross-section measurements on carbon and argon and discusses the relevant nuclear models, parametrizations and uncertainties in GENIE v3. The  $CC0\pi$  event topology is common in experiments at a few-GeV energy range. Although its main contribution comes from quasi-elastic interactions, this topology is still not well understood. The GENIE global analysis framework is exploited to analyze  $CC0\pi$  datasets from MiniBooNE, T2K and MINERvA. A partial tune for each experiment is performed, providing a common base for the discussion of tensions between datasets. The results offer an improved description of nuclear  $CC0\pi$  datasets as well as data-driven uncertainties for each experiment. This work is a step towards a GENIE global tune that improves our understanding of neutrino interactions on nuclei. It follows from earlier GENIE work on the analysis of neutrino scattering datasets on hydrogen and deuterium.

## I. INTRODUCTION

A major experimental program aims to measure neutrino-nucleus interactions over the few-GeV region. MiniBooNE was the first neutrino experiment to provide a double-differential flux-integrated  $CC0\pi$  cross-section measurement with high statistics on carbon [1]. Since then T2K [2], MicroBooNE [3] and MINERvA [4] have produced a large body of measurements on different nuclei, such as carbon or argon. However, a detailed quantitative understanding of neutrino-nucleus interactions is still missing.

In order to avoid biases in cross-section measurements due to theory assumptions, neutrino experiments focus on the study of specific topologies instead of interaction processes like Quasi-Elastic (QEL) scattering. The most dominant event topol-

ogy below the 1 GeV region is  $CC0\pi$ , which is usually defined as an event with one muon and no pions in the final state. As a consequence of the nuclear medium, different interaction processes contribute to the  $CC0\pi$  measurement. Neutrino Charged-Current (CC) QEL interactions are the dominant contribution to this topology inside the few-GeV energy range. Two-particles-two-holes (2p2h) contributions have been shown to be crucial for the correct description of the data at these kinematics. Adding to the complication, the Shallow-Inelastic Scattering (SIS) process non-trivially intermixes with other underlying mechanisms; this is due in part to the fact that pions produced after a CC REsonance Scattering (RES) interaction can be absorbed due to Final-State Interactions (FSI). Moreover, Deep-Inelastic Scattering (DIS) can also contribute, with an interplay existing between the description of DIS at slightly higher energies and the treatment of the Non-Resonant Background (NRB) in the SIS region. In GENIE we refer to the NRB as SIS, see Ref. [5]

\* publications@genie.mc.org

<sup>†</sup> Now at Tel Aviv University

for details. Figure 1 summarizes the  $\nu_\mu$   $^{12}\text{C}$  CC interaction processes and topologies of interest at the few-GeV region as a function of the neutrino energy. In addition, the flux predictions used for the cross-section measurements of MiniBooNE, MicroBooNE, T2K ND280 and MINERvA are also provided.

The GENIE Collaboration is building a global analysis of the neutrino, charged-lepton and hadron-scattering data. This comprehensive analysis of the world’s lepton-nuclear scattering data is being constructed in a staged manner, with recent efforts focused initially on the analysis of neutrino scattering on hydrogen and deuterium for the purpose of tuning aspects of the GENIE framework associated with the free-nucleon cross section: namely the SIS region [5] as well as tuning of hadronic multiplicities relevant for neutrino-induced hadronization models [9]. The present work extends this analysis campaign to a second stage: an explicit tune of nuclear model parameters to recent nuclear data.

This work is further necessitated by outstanding discrepancies between GENIE predictions and more recent datasets, which use heavy nuclei as targets. Several neutrino collaborations, such as MicroBooNE and MINERvA, tried to address these discrepancies by tuning GENIE against the  $\nu_\mu\text{CC}0\pi$  T2K and inclusive  $\nu_\mu$  CC MINERvA datasets, respectively [10–12]. All these tunes simulate 2p2h interactions with the Valencia model [13]. In both cases, the results suggest an enhancement of the 2p2h cross section. These tunes are not available for wider use within GENIE, and in some cases, these were performed with obsolete GENIE versions which differ substantially from the latest one.

In this paper, we describe the GENIE analysis of the available  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC $0\pi$  datasets from MiniBooNE, T2K, MINERvA and MicroBooNE. The main goal is to provide improved simulations tuned to nuclear data and quantify the major sources of uncertainties in CC $0\pi$  measurements. In order to do so, new degrees of freedom are developed within the GENIE Monte Carlo (MC) event generator in order to quantify the effect of variation away from the nominal models. Most of the new degrees of freedom can be used to tune other available Comprehensive Model Configurations (CMCs) in GENIE. In this analysis we focus on the ‘retuning’ of the G18\_10a\_02\_11b tune against  $\nu_\mu$ - $^{12}\text{C}$  CC $0\pi$  data from MiniBooNE, T2K and MINERvA. The G18\_10a\_02\_11b was previously tuned against free-nucleon data [5]. In this paper, we refer to G18\_10a\_02\_11b as the *nominal* tune.

All predictions shown in this paper are calculated using the G18\_10a\_02\_11b tune. G18\_10a\_02\_11b uses the Valencia model to simulate QEL and 2p2h events in the nuclear medium, while FSIs are mod-

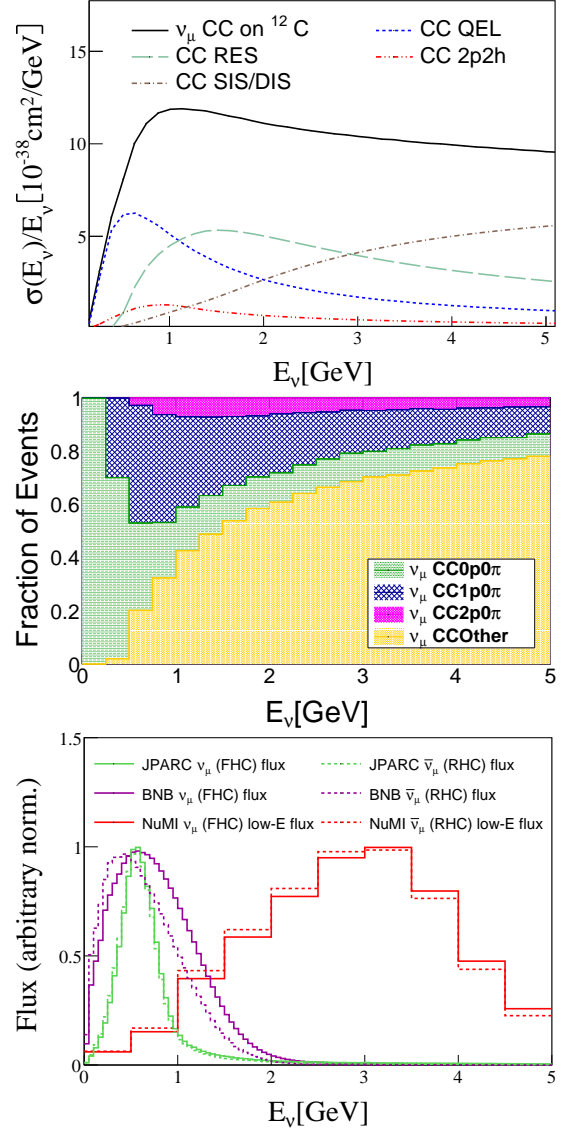


FIG. 1: (Top) Summary of contributions from each interaction process to the CC  $\nu_\mu$  cross section on  $^{12}\text{C}$  as a function of neutrino energy,  $E_\nu$ . (Middle) The corresponding fraction of the total  $\nu_\mu$ - $^{12}\text{C}$  events arising from each of the  $0\pi$  topologies. This plot assumes a momentum threshold for protons of 450 MeV/c while the GENIE predictions are obtained with the G18\_10a\_02\_11b tune. (Bottom) Summary of  $\nu_\mu$  (continuous lines) and  $\bar{\nu}_\mu$  (dashed lines) normalized flux distributions for T2K ND280 at JPARC [6], MiniBooNE and MicroBooNE with the Booster Neutrino Beam (BNB) [7], and MINERvA with the Neutrino at the Main Injector (NuMI) [8]. The flux predictions for neutrino and antineutrino modes are referred to as “Forward Horn Current (FHC)” and “Reverse Horn Current (RHC),” respectively.

TABLE I: Complete list of models used for the G18\_10a\_02\_11a tune in GENIE v3 [5].

Simulation domain	Model
Nuclear model	Local Fermi Gas [14]
QEL and 2p2h	Valencia [13, 15]
QEL Charm	Kovalenko [16]
QEL $\Delta S = 1$	Pais [17]
RES	Berger-Sehgal [18]
SIS/DIS	Bodek-Yang [19]
DIS $\Delta S = 1$	Aivazis-Tung-Olness [20]
Coherent $\pi$ production	Berger-Sehgal [18]
Hadronization	AGKY [21]
FSI	INTRANUKE hA [22]

eled using the  $hA$  model and the nuclear ground state is described with the Local Fermi Gas (LFG) model [14]. The other interaction processes are common with the free-nucleon recipe described in Ref. [5]. Tab. I details the full list of interaction processes associated with this Comprehensive Model Configuration (CMC).

We stress that G18\_10a\_02\_11b is only one of many CMCs that can be tuned within GENIE. Our main motivations behind this particular choice are: (1) we can use data-driven constraints from previous GENIE tunes on hydrogen and deuterium [5]; (2) the QEL and 2p2h processes are modeled with the Valencia model, a theory-based model which is used in most neutrino analyses; (3) FSI interactions are modeled with the INTRANUKE  $hA$  model, which is an easily tuned empirical model closely driven by hadron-nucleus scattering data. Other CMCs will be considered in future iterations of this work.

The GENIE global analysis software [5] is used to perform a partial tune for each experiment using double-differential flux-integrated  $CC0\pi$  cross-section measurements as a function of muon kinematics. We further note that only carbon datasets are considered in this work. While a more expansive study of the nuclear  $A$  dependence will be a valuable aspect of future work, this choice carries the advantage of providing a consistent basis for the exploration of statistical tensions. This work is a step closer to a global tune with neutrino-nucleus cross-section data, which can be performed using the same analysis strategy once all the tensions are well understood. Future iterations of this work will also incorporate measurements on different topologies, such as  $CC1\pi^\pm$ .

This work is organized as follows: Sec. II provides an overview of the available  $CC0\pi$  data to date. The

newly developed GENIE parameters are discussed in Sec. III. This is followed by a description of the tuning procedure in Sec. IV and a discussion of the tune results and tensions between  $CC0\pi$  and  $CCNp0\pi$  datasets in Sec. V. In addition, Sec. VI describes some modelling aspects relevant for the exploration of the  $CC0\pi$  and  $CCNp0\pi$  tension. The main conclusions of this paper are highlighted in Sec. VII.

## II. REVIEW OF NEUTRINO NUCLEUS $CC0\pi$ MEASUREMENTS

Cross-section measurements of the  $CC0\pi$  topology were carried out by SciBooNE [23], NOMAD [24], MiniBooNE [25, 26], T2K ND280 [27], MINERvA [28–30] and MicroBooNE [31, 32]. This section provides with a review of neutrino-nucleus  $CC0\pi$  data available to date.

### A. Scattering topologies and kinematics of experimental data

The  $CC0\pi$  topology is usually defined as a CC event with no pions in the final state, regardless of the number of protons in the event. However, the  $CC0\pi$  topology definition is not universal as it varies between the different published measurements as a consequence of the different detection capabilities of each experiment. In some analyses, its definition is optimized to study more exclusive final states with a specific proton multiplicity. The following nomenclature is adopted to avoid confusion for the reader: analyses requiring one or more protons in the final state are referred to as  $CCNp0\pi$ , where  $N \geq 1$ . If the analysis requires *exactly* zero or one proton in the final state,  $N$  is replaced by the corresponding number, i.e.  $CC0p0\pi$  or  $CC1p0\pi$ , respectively, for events with either no visible protons or precisely one. In some cases, the topology definition requires at least two protons in the final state. This is denoted as  $CC2p0\pi$ . We note that, in this case,  $CC2p0\pi$  events include the very small probability to have  $N > 2$  final-state protons — a scenario which is challenging to isolate experimentally. When there is no requirement on the proton multiplicity, the topology is referred to as  $CC0\pi$ . Fig. 1 presents the fraction of  $\nu_\mu$  CC events as a function of the neutrino energy for different CC topologies. In this particular plot, the  $CC0\pi$  topology contribution is broken down into more exclusive topologies depending on the proton multiplicity. It can be concluded that  $CC0\pi$  events dominate the event rate for  $E_\nu < 1.5$  GeV. At higher energies, the contribution from events with pions in the final state (CC other)

dominates.

Tab. II lists the available  $CC0\pi$  and  $CCNp0\pi$  cross section measurements to date. The table summarizes the information of interest for the evaluation of the GENIE predictions: the target type, neutrino flux mean energy and event topology definition. The neutrino flux spectrum associated with each experiment is provided in Fig. 1 (bottom) [6–8]. Both MiniBooNE and MicroBooNE use the same neutrino flux. The *kinematic quantity* column in Tab. II lists the kinematic quantities used to extract the cross-section measurements. The definition of each kinematic quantity is given in Appendix A. Some of the available measurements are double-differential or triple-differential ones. This is indicated by a comma-separated list for the kinematic quantities used in the corresponding analysis. In addition, the year of the data release and the number of bins ( $N_{\text{Bins}}$ ) for each dataset are specified. The details on the analysis requirements for MiniBooNE, T2K ND280, MINERvA and MicroBooNE datasets as well as comparisons of the G18\_10\_02\_11b predictions to the data are presented in Appendix B. The main observations from Appendix B are summarized in Sec. II B. For completeness, Tab. II includes measurements from SciBooNE and NOMAD which are not discussed further in this paper as their analysis strategy is limited with respect to the other measurements discussed in this work.

There is a now large body of  $CC0\pi$  data in the literature. This work focuses on the tuning of double differential flux-integrated  $CC0\pi$  and  $CC0p0\pi$  cross-section measurements. This is sufficient for an initial study. Additional single- and triple-differential  $CCNp0\pi$  datasets are not considered in the first iteration of this work; these will be included in future iterations. However, some comparisons are given in this paper.

## B. Dataset overview and initial considerations

The need for a tuning exercise for GENIE is clear. A few comparisons of G18\_10a\_02\_11b against the available nuclear data are shown here and the remaining plots are in Appendix A. In general,  $CC0\pi$  and  $CC0p0\pi$  datasets are under-predicted, whilst the  $CCNp0\pi$  datasets are in good agreement with the *nominal* predictions. This can be seen in Figs. 2 to 4. MiniBooNE  $CC0\pi$  (Fig. 2) and T2K ND280  $CC0p0\pi$  data are both under-predicted at muon backward angles, where the contribution to the prediction is mostly from CCQEL events. At forward angles, where the contribution from non-CCQEL events is significant, the data are also under-predicted. The disagreement with MIN-

ERvA  $CC0\pi$  data are most significant in the region where 2p2h events dominate,  $0.15 < p_T < 0.7$  GeV, see Fig. 3. Single-Transverse Kinematic Imbalance (STKI) variables [37] bring in new sensitivities and comparisons against MINERvA data are shown in Fig. 4. Non-QEL events and FSI contributions dominate the region of high  $\delta p_T$  and  $\delta \alpha_T$ . These contributions are essential to describe the data.

The G18\_10a\_02\_11b predictions as a function of the leading proton momentum show a dependency of 2p2h with  $W$ : at high proton momentum, 2p2h events with  $W > M_\Delta = 1232$  MeV/ $c^2$  dominate, whilst the opposite is true at low momentum. This is highlighted in Fig. 4a. 2p2h events contributing to the T2K ND280  $CC0p0\pi$  sample (Fig. 5) have  $W < W_{\text{Dip}} = 1120$  MeV/ $c^2$ . Higher multiplicity samples have a significant contribution from 2p2h events with  $W > W_{\text{Dip}}$ . The contribution from 2p2h events with  $W < M_N = 938$  MeV/ $c^2$  is negligible for all the analyses discussed in this paper.

For further comparisons to data, see Appendix B.

## III. DISCUSSION OF $CC0\pi$ MODEL IMPLEMENTATION IN GENIE

This section describes the parameters available to most directly influence  $CC0\pi$  predictions within G18\_10a\_02\_11b. The parameters selected for this analysis are optimized for the G18\_10a\_02\_11a tune. The complete list of parameters is shown in Tab. III. The parameter ranges of interest used for the Professor parametrization are also provided. These can be grouped into five categories: CCQEL, CCSIS, CC2p2h, FSI or nuclear model parameters.

Not all the parameters from Tab. III have been included in the analysis presented in this paper. Only the parameters included in the final tune are described in this section. Other parameters of interest to tune  $CC0\pi$  data that have been excluded from this analysis are described in Appendix C. The reasons for excluding these parameters are summarized in Appendix C 3.

Most of these parameters can be applied to other CMCs [5]. We strive to have as many common, model-independent parameters to allow for systematic comparison between CMCs, but this is not always possible. An extension of this work to other CMC will be a subject of a future paper.

### A. Charged-current quasi-elastic implementation

The QEL cross section at the free-nucleon level is parametrized with the QEL axial mass,  $M_A^{\text{QEL}}$ ,

TABLE II: Summary of CC0 $\pi$  analyses of  $\nu_\mu$  and  $\bar{\nu}_\mu$  interactions on nuclei. For each analysis, information on the neutrino flux mean energy, target type and event topology is provided. The *kinematic quantity* column specifies the list of kinematic quantities used in the cross-section measurement. Integrated cross-section measurements are denoted with a “—”. All kinematic quantities are defined in Appendix. A. The last column specifies whether the dataset is considered in the analysis.

Experiment	$\langle E_\nu \rangle$	Target	Topology	Kinematic quantity	$N_{\text{Bins}}$	Year	Ref.	
$\nu_\mu$ -A measurements								
SciBooNE	700 MeV	$^{12}\text{C}$	CC0 $\pi$	$E_\nu^{\text{QEL}}$	5	2006	[23]	×
NOMAD	23 GeV	$^{12}\text{C}$	CC0 $\pi$	$E_\nu^{\text{QEL}}$	10	2009	[24]	×
MiniBooNE	788 MeV	$^{12}\text{C}$	CC0 $\pi$	$T_\mu, \cos \theta_\mu$	137	2010	[25]	✓
				$Q_{\text{QEL}}^2$	17			
				$E_\nu^{\text{QEL}}$	14			
T2K ND280	600 MeV	$^{12}\text{C}$	CC0p0 $\pi$	$p_\mu, \cos \theta_\mu$	60	2018	[27]	✓
---	600 MeV	$^{12}\text{C}$	CC1p0 $\pi$	$\cos \theta_\mu, \cos \theta_p, p_p$	40	2018	[27]	×
---	600 MeV	$^{12}\text{C}$	CC2p0 $\pi$	—	1	2018	[27]	×
---	600 MeV	$^{12}\text{C}$	CCNp0 $\pi$	$\delta p_T$	8	2018	[27]	×
				$\delta \phi_T$	8			
				$\delta \alpha_T$	8			
				$\Delta p_p, \cos \theta_\mu, p_\mu$	49			
				$ \Delta \mathbf{p}_p , \cos \theta_\mu, p_\mu$	49			
				$\Delta \theta_p, \cos \theta_\mu, p_\mu$	35			
MINERvA	3.5 GeV	$^{12}\text{C}$	CC0 $\pi$	$p_T^\mu, p_L^\mu$	144	2019	[28]	✓
				$Q_{\text{QEL}}^2$	16			
				$E_\nu^{\text{QEL}}$	12			
---	3.5 GeV	$^{12}\text{C}$	CCNp0 $\pi$	$p_p$	25	2018	[29]	✓
				$\theta_p$	26			
				$\delta p_T$	24			
				$\delta \alpha_T$	12			
				$\delta \phi_T$	18			
---	3.5 GeV	$^{12}\text{C}$	CCNp0 $\pi$	$\delta p_{Tx}$	32	2020	[30]	×
				$\delta p_{Ty}$	33			
---	6 GeV	$^{12}\text{C}$	CC0 $\pi$	$p_T^\mu, p_L^\mu$	184	2020	[33]	×
				$Q_{\text{QEL}}^2$	19			
---	6 GeV	$^{12}\text{C}$	CCN0 $\pi$	$p_T^\mu, p_L^\mu, \sum T_p$	660	2022	[34]	×
				$E_\mu, q_0^{\text{QEL}}, \sum T_p$	540			
MicroBooNE	800 MeV	$^{40}\text{Ar}$	CC1p0 $\pi$	$p_\mu$	7	2020	[31]	×
				$\cos \theta_\mu$	7			
				$p_p$	7			
				$Q_{\text{QEL}}^2$	7			
				$E_\nu^{\text{cal}}$	7			
---	800 MeV	$^{40}\text{Ar}$	CCNp0 $\pi$	$p_\mu^{\text{reco}}$	10	2020	[35]	×
				$\cos \theta_\mu^{\text{reco}}$	12			
				$p_p^{\text{reco}}$	10			
				$\cos \theta_p^{\text{reco}}$	9			
				$\theta_{\mu p}^{\text{reco}}$	6			
$\bar{\nu}_\mu$ -A measurements								
NOMAD	23 GeV	$^{12}\text{C}$	CC0 $\pi$	$E_\nu^{\text{QEL}}$	6	2009	[24]	×
MiniBooNE	665 MeV	$^{12}\text{C}$	CC0 $\pi$	$T_\mu, \cos \theta_\mu$	78	2013	[26]	✓
				$Q_{\text{QEL}}^2$	16			
				$E_\nu^{\text{QEL}}$	14			
MINERvA	3.5 GeV	$^{12}\text{C}$	CC0p0 $\pi$	$p_T^\mu, p_L^\mu$	60	2013	[36]	✓
				$Q_{\text{QEL}}^2$	8			
				$E_\nu^{\text{QEL}}$	10			

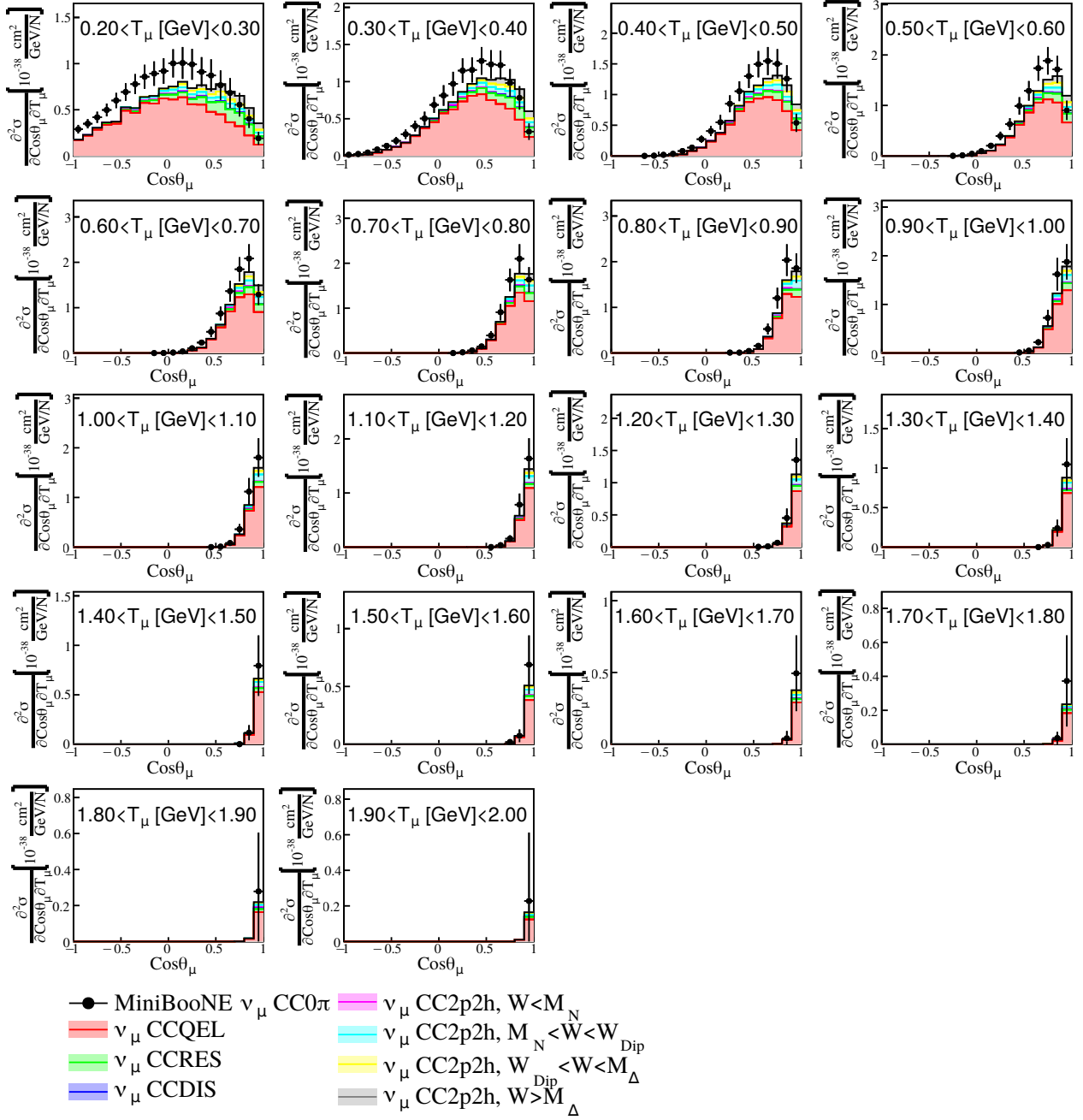


FIG. 2: MiniBooNE  $\nu_\mu$  CC0 $\pi$  double differential flux-averaged cross section as a function of the muon angle ( $\theta_\mu$ ) and kinetic energy ( $T_\mu$ ) [25]. The corresponding slices on  $T_\mu$  are compared against the G18\_10a\_02.11b tune. The GENIE prediction is divided into different interaction modes.

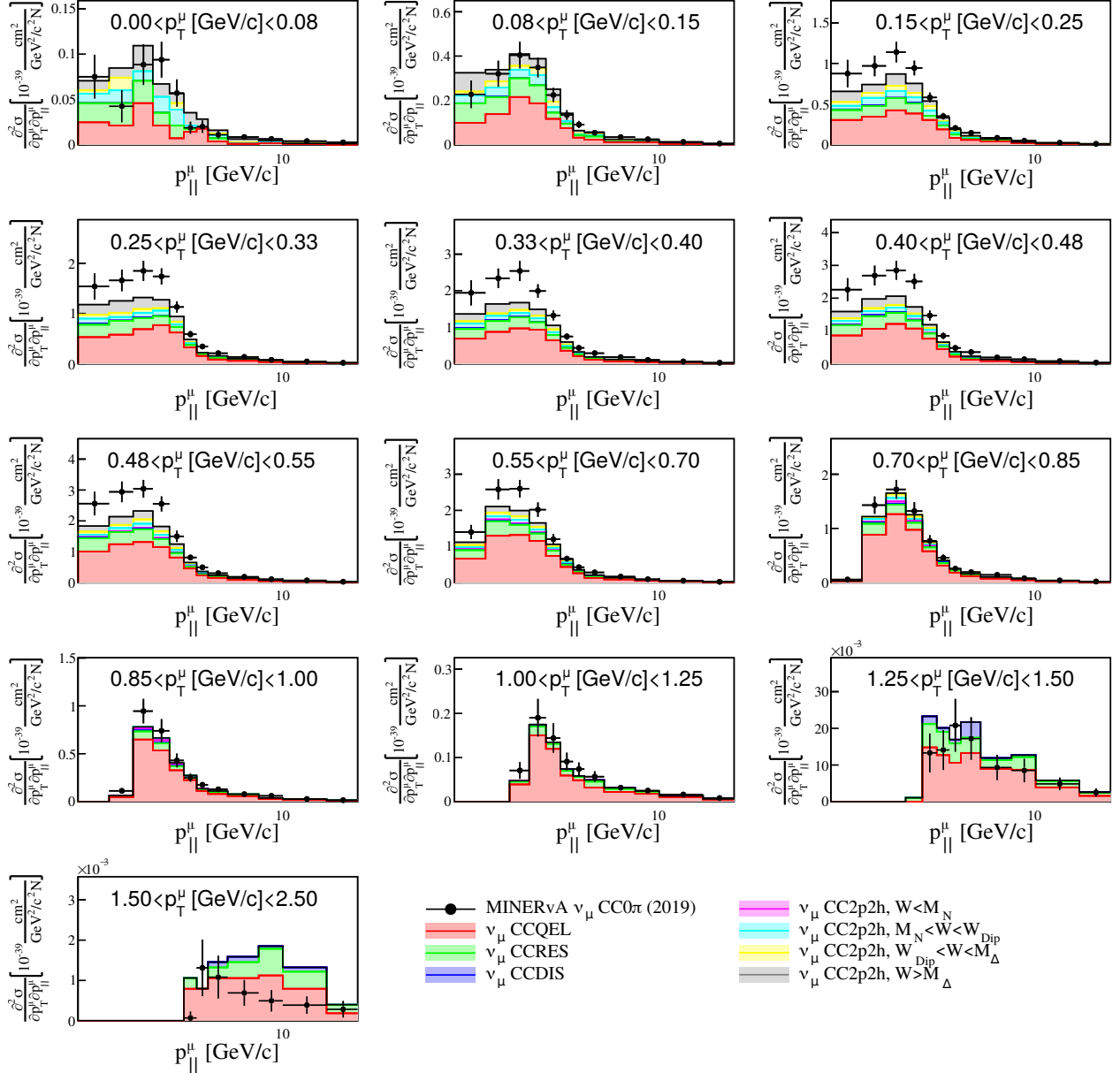


FIG. 3: MINERvA  $\nu_\mu$  CC0 $\pi$  double differential flux-averaged cross-section as a function of the muon longitudinal momentum,  $p_{||}$ , and transverse momentum,  $p_T$  [28]. The corresponding slices on  $p_T$  are compared against the G18\_10a\_02\_11b tune. The GENIE prediction is divided into different interaction modes.

and a QEL scaling factor,  $S_{\text{QEL}}$ . Both parameters are common in the simulation of neutrino interactions on free nucleons and nuclei.  $M_A^{\text{QEL}}$  appears as the main degree of freedom in the widely-used dipole parametrization of the QEL form factor. We point out that more elaborate CMCs based on the z-expansion model [39] are now available in GENIE. In this work, preference is given to tune  $M_A^{\text{QEL}}$  as hydrogen and deuterium data provide informative priors to help constrain this parameter [5].

The QEL cross section is affected by the dynamics of the nuclear medium. We include long-range nucleon-nucleon correlations in our calculations with the Random-Phase Approximation (RPA) correction [15]. The main effect of the RPA correction is a suppression of the QEL cross section at low  $Q^2$ . This correction is well supported by data and theory, but models differ in predicting its exact strength. This uncertainty is incorporated in GENIE with two parameters: one to scale the nominal QEL cross-

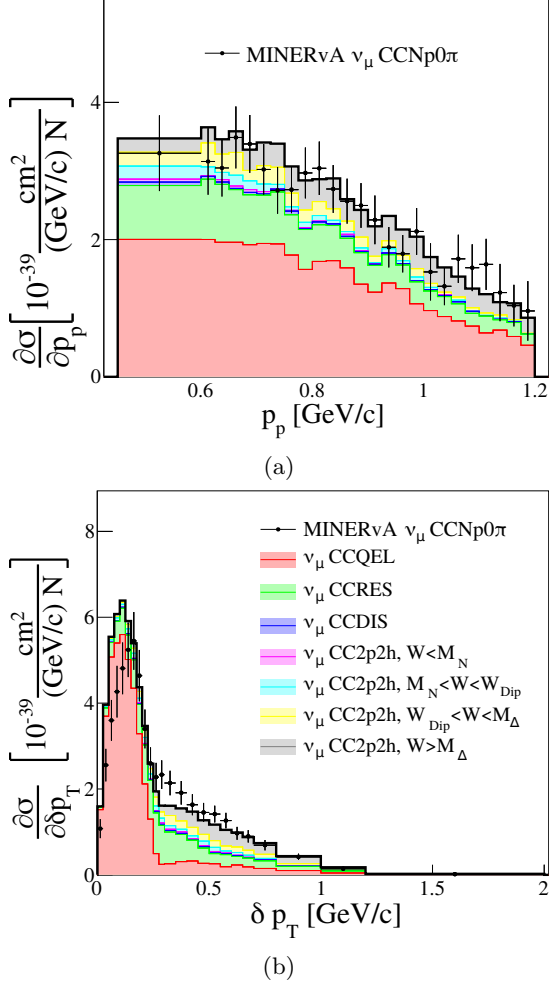


FIG. 4: MINERvA  $\nu_\mu$  CCNp0 $\pi$  differential flux-averaged cross-section as a function of the leading-proton momentum,  $p_p$  (a), and the STKI variable [29, 30]  $\delta p_T$  (b). The data are compared against the G18.10a.02.11b tune. The GENIE prediction is divided into interaction modes.

section prediction with RPA corrections,  $\omega_{\text{RPA}}$ , and the other one to scale the QEL cross section without RPA corrections,  $\omega_{\text{NoRPA}}$ . The total QEL cross section is calculated as a linear combination of the cross-section with and without RPA corrections:

$$\sigma^{\text{QEL}} = \omega_{\text{RPA}} \cdot \sigma_{\text{RPA}}^{\text{QEL}} + \omega_{\text{NoRPA}} \cdot \sigma_{\text{NoRPA}}^{\text{QEL}}. \quad (1)$$

This parametrization can be used to scale the QEL cross section when  $\omega_{\text{RPA}} + \omega_{\text{NoRPA}} \neq 1$ . If  $\omega_{\text{NoRPA}} = 0$ ,  $\omega_{\text{RPA}}$  has the exact same effect as  $S_{\text{QEL}}$ . Therefore,  $S_{\text{QEL}}$  is not included in the tune. One benefit of this approach is that possible scaling factors on the RPA parametrization do not alter the agreement with free-nucleon data. In addition, it reduces the analysis computing time. In Fig. 6, the CC

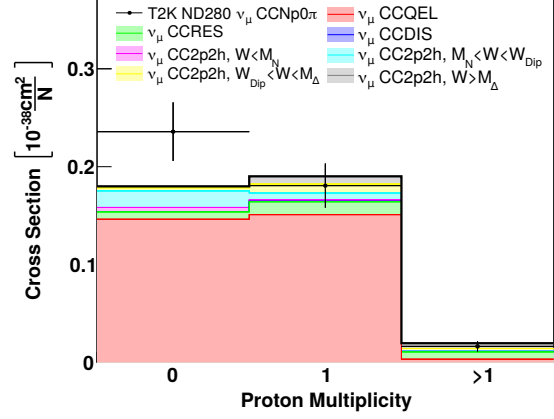


FIG. 5: T2K ND280 flux-averaged  $\nu_\mu$  CCNp0 $\pi$  differential cross section as a function of the proton multiplicity [38]. The data are compared against the G18.10a.02.11b tune. The GENIE prediction is divided into different interaction modes.

TABLE III: Summary of parameters relevant for CC0 $\pi$  analysis. The range of interest, nominal value in GENIE v3 is also shown. The range of interest corresponds to the parameter space used for the Professor parametrization [5]. (–) is used for parameters that are excluded in the analysis.

The range for the parameters considered in the Professor parametrization but not used in the final tune is not reported. In such cases, the parameters are fixed to the corresponding nominal values (in parenthesis) in the final analysis, described in Sec. IV. The last column specifies whether the parameter is considered in the final analysis.

Parameter	Nominal Value	Range	In Final Tune
$M_A^{\text{QEL}}$ (GeV/c <sup>2</sup> )	$1.00 \pm 0.01$	[0.97, 1.18]	✓
$S_{\text{QEL}}$	1	–	✗
$\omega_{\text{RPA}}$	1	[–0.5, 1.5]	✓
$\omega_{\text{NoRPA}}$	0	[–0.5, 1.5]	✓
$M_A^{\text{RES}}$ (GeV/c <sup>2</sup> )	$1.09 \pm 0.014$	–	✗
$S_{\text{RES}}$	$0.84 \pm 0.03$	[0.5, 1.5]	✓
$R_{\nu p}^{\text{CC}1\pi}$	0.008	–	✗
$R_{\nu n}^{\text{CC}1\pi}$	$0.94 \pm 0.075$	–	✗
$R_{\nu p}^{\text{CC}2\pi}$	$0.03 \pm 0.01$	–	✗
$R_{\nu n}^{\text{CC}2\pi}$	$2.3 \pm 0.12$	–	✗
$S_N^{2p2h}$	1	[0, 2]	✓
$S_\Delta^{2p2h}$	1	[0, 2]	✓
$S_{pL}^{2p2h}$	1	[0, 2]	✓
$S_{Ab\pm}^{\pi^\pm}$	1	(1)	✗
$S_{MFP}^{\pi^\pm}$	1	(1)	✗
$f^{\text{QEL}}$	0	(0)	✗
$f^{2p2h}$	0	(0)	✗



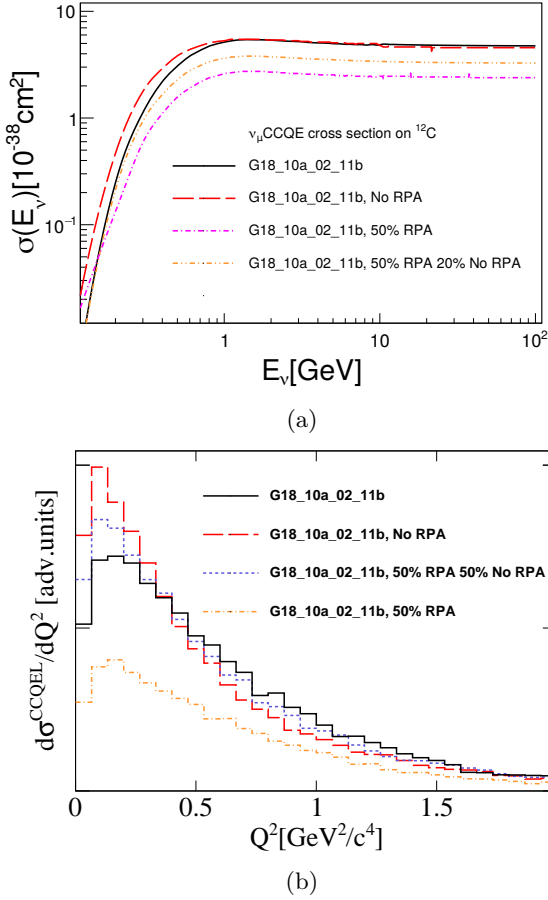


FIG. 6: Impact of the RPA parametrization on the CCQEL cross section. The G18\_10a\_02\_11b prediction is shown in black. The other predictions are obtained with the same tune while changing the RPA weight values. (a) Total CCQEL cross section for  $^{12}\text{C}$ . (b) Flux-integrated differential cross section as a function of  $Q^2$ . The prediction is obtained with the NuMI flux in low-energy mode.

QEL cross section as a function of the neutrino energy is shown for different combinations of  $\omega_{\text{RPA}}$  and  $\omega_{\text{No RPA}}$ .

Choosing each parameter range of interest is crucial for the correct evaluation of the post-fit uncertainties. In some cases, such as for  $\omega_{\text{No RPA}}$ , we sample negative values to allow the best-fit result to be at its physical limit of 0. In the case of the RPA parametrization, we impose the additional condition that  $0.4 < \omega_{\text{RPA}} + \omega_{\text{No RPA}} < 1.6$  in the sampling on the phase space so that  $\sigma^{\text{QEL}} > 0$ . Fig. 7 shows the distribution of sampled parameter values for  $\omega_{\text{RPA}}$  and  $\omega_{\text{No RPA}}$ . Notice that the two limit cases are at the centre of the phase space.

It is desirable to apply priors to  $\omega_{\text{RPA}}$  and

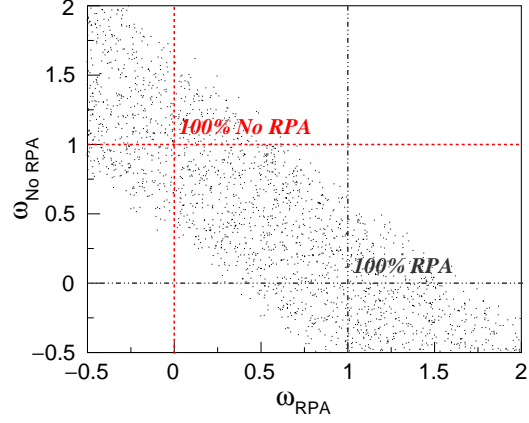


FIG. 7: Distribution of scan points used for the GENIE tune in the  $\omega_{\text{RPA}}$  vs  $\omega_{\text{No RPA}}$  phase space. The grey (red) line intersection highlights the limit case in which we consider 100% (0%) of the RPA strength. This plot shows a total of 2,050 scan points distributed uniformly. The parameter ranges considered are those from Tab. III.

$\omega_{\text{No RPA}}$ , as effectively, parameter combinations for which  $\mathcal{S}_{\text{RPA}} \equiv \omega_{\text{RPA}} + \omega_{\text{No RPA}} \neq 1$  act as a scaling of the QEL cross section. Hydrogen and deuterium QEL cross-section measurements are compatible with  $\mathcal{S}_{\text{RPA}} = 1$ . However, nuclear effects might introduce an uncertainty in the scaling. A possible way to include this information is to consider uncorrelated priors on the sum,  $\mathcal{S}_{\text{RPA}}$ , and the difference,  $\Delta_{\text{RPA}} \equiv \omega_{\text{RPA}} - \omega_{\text{No RPA}}$ ,

$$\begin{aligned} \mathcal{S}_{\text{RPA}} &= 1 \pm \sigma_{\mathcal{S}}, \\ \Delta_{\text{RPA}} &= 1 \pm \sigma_{\Delta}, \end{aligned}$$

with  $\sigma_{\mathcal{S}}$  and  $\sigma_{\Delta}$  being the variance associated with the priors on  $\mathcal{S}_{\text{RPA}}$  and  $\Delta_{\text{RPA}}$ , respectively. In terms of  $\omega_{\text{RPA}}$  and  $\omega_{\text{No RPA}}$ , this approach includes a correlation between these parameters:

$$\Sigma_{\text{RPA}} = \frac{1}{4} \begin{pmatrix} \sigma_{\mathcal{S}}^2 + \sigma_{\Delta}^2 & \sigma_{\mathcal{S}}^2 - \sigma_{\Delta}^2 \\ \sigma_{\mathcal{S}}^2 - \sigma_{\Delta}^2 & \sigma_{\mathcal{S}}^2 + \sigma_{\Delta}^2 \end{pmatrix} \quad (2)$$

This correlation between  $\omega_{\text{RPA}}$  and  $\omega_{\text{No RPA}}$  is included in the tune. The corresponding central values are  $\mu_{\text{RPA}} = 1$  and  $\mu_{\text{No RPA}} = 0$  respectively. The  $\sigma_{\mathcal{S}}$  and  $\sigma_{\Delta}$  are determined from previous tune iterations, see Sec. C 3. As concluded from Sec. II, some flexibility in the QEL scaling may be required to describe the data, hence, in this analysis  $\sigma_{\mathcal{S}} = 0.2$ . This method requires that we impose a prior on  $\Delta_{\text{RPA}}$  as well. Such prior affects the strength of the RPA correction, which we aim to constrain from

data. In order to avoid strong constraints on  $\Delta_{\text{RPA}}$ ,  $\sigma_{\Delta} = 5$ .

A similar RPA parametrization was used in the latest theory-driven MicroBooNE tune [10]. The MicroBooNE Collaboration employed the GENIE ReWeight package to parametrize the RPA effect as a linear combination from the QEL cross section with the RPA correction to the QEL cross section without RPA using a single parameter limited to  $[0,1]$ . We refer to this tune as  $\mu\text{BooNE}$  tune. Both approaches are equivalent when  $\mathcal{S}_{\text{RPA}} = 1$ .

### B. Charged-current multi-nucleon implementation

The tuning of 2p2h models takes a central role in this work. As discussed in Sec. II, untuned GENIE CC0 $\pi$  G18.10a.02\_11b predictions underestimate the data in regions where 2p2h events contribute.

Previous tuning attempts by other neutrino collaborations indicate a preference for a higher 2p2h cross section. The simplest approach to enhance 2p2h is to use a global scaling factor. We refer to this parameter as  $S_{2\text{p}2\text{h}}$ . MINERvA opted for an empirical approach where they add an extra Gaussian contribution to enhance 2p2h interactions in  $q_0$  and  $q_3$ . This is tuned to MINERvA CC inclusive data. This tune is known as  $\text{Mn}\nu\text{GENIE}$  v1 tune [40, 41]. The  $\mu\text{BooNE}$  tune incorporates the 2p2h cross-section uncertainty with a linear extrapolation between the GENIE 2p2h Empirical and Valencia model to account for possible shape differences. In addition,  $S_{2\text{p}2\text{h}}$  is also considered.

Different GENIE 2p2h models predict a slightly different strength and shape for the 2p2h cross section [42]. These differences motivated the development of a new parametrization that is able to modify the strength as well as the shape of the cross section in the  $q_0$ - $q_3$  space. This is accomplished by scaling the 2p2h cross section a function of  $W$ :

$$\sigma^{2\text{p}2\text{h}} \rightarrow S(W) \cdot \sigma^{2\text{p}2\text{h}} \quad (3)$$

$S(W)$  is the scaling function and  $\sigma^{2\text{p}2\text{h}}$  the *nominal* cross section calculation.

The scaling function,  $S(W)$ , depends linearly on  $W$ . In this work, the scaling function is optimized for the Valencia model which has two characteristic peaks in the  $q_0$ - $q_3$  space, as it can be seen in Fig. 8. The peaks are situated at  $W = M_N$  and  $W = M_{\Delta}$ . The dip between the two peaks is at  $W_{\text{Dip}}$ . This is implemented by imposing the following boundary conditions:

- $S_{PL,\text{min}}^{2\text{p}2\text{h}} \equiv S(W = W_{PL,\text{min}})$

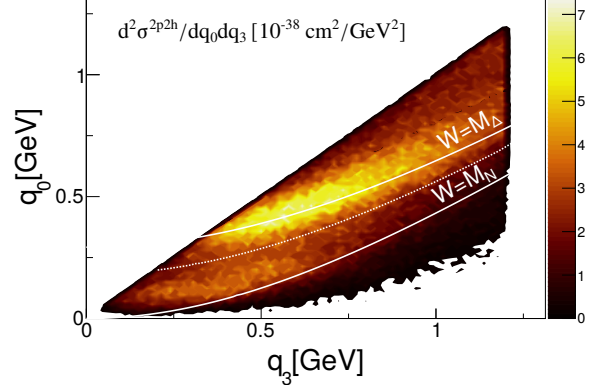


FIG. 8: Double-differential  $\nu_{\mu}$ - $^{12}\text{C}$  CC2p2h cross section from the Valencia model in GENIE. Lines of constant  $W$  at  $W = M_N = 938 \text{ MeV}/c^2$ ,  $W = M_{\text{Dip}} = 1120 \text{ MeV}/c^2$  (dotted line) and  $W = M_{\Delta} = 1232 \text{ MeV}/c^2$  are also shown.

- $S_N^{2\text{p}2\text{h}} \equiv S(W = M_N)$
- $S_{\text{Dip}}^{2\text{p}2\text{h}} \equiv S(W = W_{\text{Dip}})$
- $S_{\Delta}^{2\text{p}2\text{h}} \equiv S(W = M_{\Delta})$
- $S_{PL,\text{max}}^{2\text{p}2\text{h}} \equiv S(W = W_{PL,\text{max}})$

The  $S^{2\text{p}2\text{h}}$  parameters are referred to in this work as 2p2h scaling parameters. The limits of the 2p2h phase space are defined by  $W_{PL,\text{min}}$  and  $W_{PL,\text{max}}$ . The upper limit is obtained by simply imposing  $Q^2 = 0$ . The lower limit is parametrized as a function of  $q_0$  and  $q_3$ . In all GENIE v3 CMCs, the 2p2h scaling parameters are set to 1.

Only three out of the five 2p2h scaling parameters are included in the tune:  $S_N^{2\text{p}2\text{h}}$ ,  $S_{\Delta}^{2\text{p}2\text{h}}$  and  $S_{PL,\text{max}}^{2\text{p}2\text{h}}$ . Events with  $W < M_N$  are negligible for all CC0 $\pi$  measurements of interest for this work, hence,  $S_{PL,\text{min}}^{2\text{p}2\text{h}}$  is not included in the tune. In addition,  $S_{\text{Dip}}^{2\text{p}2\text{h}}$  is also not included as the region between  $N$  and  $\Delta$  peaks is too narrow in  $W$  and the data cannot be sensitive to such parameter. In order to facilitate readability, the  $S_{PL,\text{max}}^{2\text{p}2\text{h}}$  parameter is redefined as  $S_{PL}^{2\text{p}2\text{h}}$ . In the particular case of T2K ND280, variations of  $S_{\Delta}^{2\text{p}2\text{h}}$  and  $S_{PL}^{2\text{p}2\text{h}}$  do not affect the CC0p0 $\pi$  predictions. This is highlighted in Fig 5, where only events with  $W < W_{\text{Dip}}$  contribute to the 2p2h cross section prediction with no protons above the detection threshold. Therefore, these parameters are not included when tuning against T2K ND280 CC0p0 $\pi$  data.

The dependency of the scaling function with  $W$  for a particular set of parameters is shown in Fig. 9 (top). This particular example enhances (suppresses) the 2p2h cross-section peak in the  $W = M_N$  ( $W = M_{\Delta}$ ) region. The example scaling function

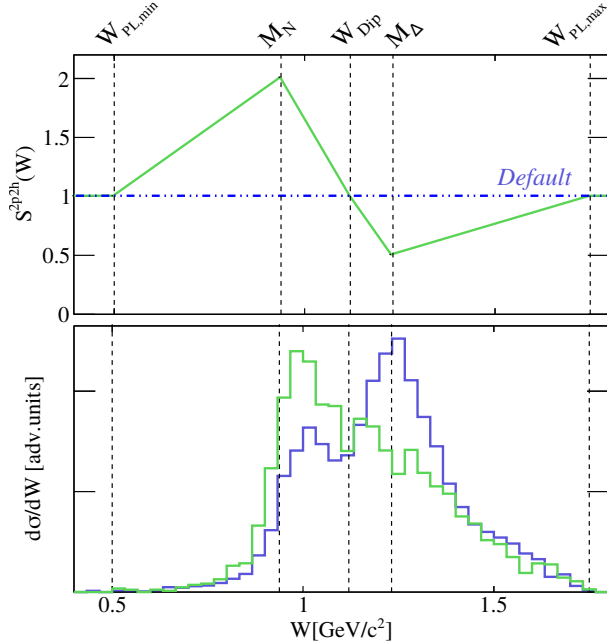


FIG. 9: Graphic representation of the 2p2h scaling as a function of  $W$ . On the top, the *default* parametrization (dashed blue) and an example scaling function (green) are shown. The highlighted dashed vertical lines correspond to the tunable scaling parameters for  $W = W_{PL}^{\min}$ ,  $M_N$ ,  $W_{Dip}$ ,  $M_{\Delta}$ , and  $W_{PL}^{\max}$ . The bottom figure shows the Valencia 2p2h flux-integrated cross section as a function of  $W$  for the G18\_10a.02\_11b tune in blue, and the same prediction scaled with the example scaling function in green. This plot is obtained simulating  $\nu_{\mu}$  interactions on  $^{12}\text{C}$  with the NuMI  $\nu_{\mu}$  low energy configuration [8].

considers  $S^{2p2h}(M_N) = 2$ ,  $S^{2p2h}(M_{\Delta}) = 0.5$ , and  $S^{2p2h}(W_{PL,\min}) = S^{2p2h}(W_{Dip}) = S^{2p2h}(W_{PL,\max}) = 1$ . The effect on the predictions of interest for this paper depends on the neutrino energy, proton multiplicity and proton momenta, as discussed in Sec. II.

### C. Charged-current shallow-inelastic implementation

SIS events also contribute to the  $\text{CC}0\pi$  signal as pions can be absorbed by the nuclear medium. Therefore, SIS mismodeling impacts the interpretation of the measurements and must be considered in the tune. The parameters available in GENIE to modify the RES and NRB background are:

1. RES axial mass,  $M_A^{\text{RES}}$ ;
2. RES scaling factor,  $S_{\text{RES}}$ ;

3. SIS scaling parameters that depend on the initial state,  $R_{\nu p}^{\text{CC}1\pi}$ ,  $R_{\nu n}^{\text{CC}1\pi}$ ,  $R_{\nu p}^{\text{CC}2\pi}$ ,  $R_{\nu n}^{\text{CC}2\pi}$ .

These parameters have been previously tuned against hydrogen and deuterium data [5].

This is a lesser issue for MiniBooNE and T2K ND280  $\text{CC}0\pi$  data, more significant for the higher energy MINERvA data. Nuclear effects in SIS and DIS remain imperfectly understood and are therefore an important open area, both for the current study as well as future neutrino-nuclear interaction research. Nuclear-medium effects were studied for pion and electron beams [43] and found to be moderately significant.

The  $S_{\text{RES}}$  parameter is the only SIS parameter included in the  $\text{CC}0\pi$  tune. NRB parameters are not included: single pion NRB parameters have a small impact on the  $\text{CC}0\pi$  predictions. In addition, higher multiplicity SIS/DIS contributions are negligible. In later instances, we refer to SIS/DIS contributions as DIS.

### D. Discussion

The choice of tuning parameters is always complicated as these must sample the core physics dependencies with minimal correlation. In the  $\mu\text{BooNE}$  tune [10], only four parameters were used with an emphasis on RPA and 2p2h modeling. Although the RPA and 2p2h components are still important here, additional parameters are used to examine these aspects more fully. Since this exercise uses a broader range of neutrino energy, more parameters are needed to account for pion production. However, this contribution is small at neutrino energies  $\sim 1$  GeV and, although larger for MINERvA, we find that a single normalization parameter is sufficient to describe the  $\text{CC}0\pi$  data included in this study. Additional potential parameters are introduced here and discussed more fully in Appendix C.

Similarly, as we discuss in more detail in Sec. IV D, there can in principle be nonnegligible correlations among the parameters associated with the nuclear models tuned in this current study and those associated with single-nucleon degrees of freedom as explored in Ref. [5]. A possible approach is to fit both sets of parameters comprehensively. In the present work we concentrate on a more targeted partial tune of these nuclear parameters in order to map their relationship to the corresponding data taken on nuclear targets. This is further justified by the fact that the leading sensitivity to the nuclear parameters is provided by the nuclear data fitted here. Ultimately, however, performing nuclear tunes with frozen single-nucleon parameters can be expected to

influence the resulting nuclear tune through the correlations mentioned above; systematically disentangling these correlations will require a more global comprehensive tune involving simultaneous fits of both types of data, an undertaking which will be informed by the present study with respect to model priors, methodology, and an understanding of compatibility of nuclear data sets explored in partial tunes as discussed below.

In terms of specific nuclear model choices, the nuclear binding energy is a complicated topic that we quantify through a single number in existing GENIE models which is independent of the momentum distribution. This is adequate for inclusive electron scattering [44]. In more sophisticated treatments of semi-exclusive data, the binding energy and the missing momentum are interrelated via spectral functions [45]. Any binding energy parameters are found to be highly correlated with the other parameters chosen for tuning. We choose to leave this out of the tuning procedure and show the effect of these parameters in Appendix C.

Similarly, FSI has been studied for many years and there are many disagreements about the proper treatment [46]. Although this is a natural aspect of a full tune, the CC0 $\pi$  data are not particularly sensitive to this aspect; FSI parameters are most sensitive to CCNp0 $\pi$  data. A global analysis of CC0 $\pi$  and CCNp0 $\pi$  is out of the scope of this analysis and it is left for future iterations of this work. We show some interesting CCNp0 $\pi$  sensitivities in Appendix C.

#### IV. TUNING PROCEDURE

This section summarizes the tuning procedure for the analysis. The main goal is to tune GENIE against MiniBooNE, T2K ND280 and MINERvA CC0 $\pi$  data.

##### A. Construction of the GENIE prediction

In order to build the prediction associated with each dataset specified in Sec. II, we generate  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC events for the experiment target using the neutrino fluxes from Fig. 1. In this work, the events are generated with the G18\_10a\_02\_11b tune [5].

To compute the prediction associated with the  $i$ th dataset, we generate  $N_i^{\text{TOT}}$  events. Events that do not satisfy the corresponding selection criteria specified in Sec. II are rejected. The number of accepted events in the  $j$ th bin is  $N_j^i(\boldsymbol{\theta})$ .  $\boldsymbol{\theta}$  is the vector of tunable parameters specified in Tab. III.

We build the corresponding  $n$ -differential flux-integrated cross section prediction for a given set

of observables,  $O$ , as

$$\left(\frac{\partial^n \sigma_{th}(\boldsymbol{\theta})}{\partial O^n}\right)_j^i = \frac{N_j^i(\boldsymbol{\theta})}{\Phi_i N_i^{\text{TOT}} \Delta O_j^i} \times \int dE_\nu \frac{d\phi_i}{dE_\nu} \sum_{T_i} R_{T_i} \sigma_{T_i}(E_\nu, \boldsymbol{\theta}),$$

where  $\Phi_i$  is the integrated flux for the  $i$ th dataset,  $\Delta O_j^i$  corresponds to the  $j$ th  $n$ -dimensional bin volume for the quantities used in the differential cross section calculation, and  $d\phi/dE_\nu$  is the expected flux at a given neutrino energy. For a target mix, the averaged cross section is evaluated by summing over the nucleus type in the target mix,  $T_i$ . The ratio of a specific nucleus type with respect to the total nuclei is  $R_{T_i}$  and  $\sigma_{T_i}(E_\nu)$  is the total cross section for a given nucleus type.

##### B. Avoiding the Peele's Pertinent Puzzle

The bin-to-bin covariance matrix provided by each experiment is considered in the evaluation of the  $\chi^2$ . The T2K ND280, MicroBooNE and MINERvA datasets have highly correlated bin-to-bin covariance matrices. Previous attempts to fit neutrino-nucleus data using the full covariance matrices result in a significant reduction of the cross section [10, 47, 48]. These results are not surprising in highly correlated bins ( $\rho > 60\%$ ) in the Gaussian approximation [49]. This is known as Peele's Pertinent Puzzle (PPP) [49, 50].

To avoid PPP, we change our variables in order to reduce the correlation for the  $i$ th dataset using the following prescription:

$$Z_j^i \equiv \begin{cases} \sum_k D_k^i & j = 0, \\ D_j^i & 0 < j < N_i. \end{cases} \quad (4)$$

$D_{ij}$  corresponds to the  $i$ th dataset mean value at the  $j$ th bin. The  $j$ th and  $k$ th indices run over the number of bins associated with the  $i$ th dataset. This is known as Norm-Shape (NS) transformation. After the NS transformation, the integral is moved into the first bin of the  $i$ th dataset, whilst the rest describes the shape distribution. This transformation is applied to both data and predictions.

The bin-to-bin covariance associated with the  $i$ th dataset,  $\Sigma_D(\mathbf{D})_{jk}^i$ , transforms as follows:

$$\Sigma_{NS}(\mathbf{Z})_{jk}^i \equiv \left[ \left( \frac{d\mathbf{Z}}{d\mathbf{D}} \right) \Sigma_D(\mathbf{D}) \left( \frac{d\mathbf{Z}}{d\mathbf{D}} \right)^T \right]_{jk}^i, \quad (5)$$

where

$$\left(\frac{d\mathbf{Z}}{d\mathbf{D}}\right)_{ja}^i = \begin{cases} 1 & j = 0 \\ \frac{\delta_{ja} \left(\sum_k D_k^i\right) - D_j^i}{\left(\sum_k D_k^i\right)^2} & 0 < j < N_i. \end{cases} \quad (6)$$

After the NS transformation the relative uncertainties are constant when the normalization changes.

The same transformation is applied to the prediction mean values and covariance. Before the NS transformation, the prediction covariance only has diagonal elements. This is not true after the NS transformation. However, the off-diagonal elements on the prediction covariance are small and are neglected in this work. The prediction central values and errors after the NS transformation are denoted as  $Y_j^i(\theta)$  and  $\delta Y_j^i(\theta)$  respectively.

### C. Professor parametrization

Given that performing a multi-parameter brute-force scan is not feasible, we use Professor [51] to parametrize the behavior of our predicted cross section and error in each bin in the NS space. We refer to this quantities as  $\tilde{Y}_j^i(\theta)$  and  $\delta\tilde{Y}_j^i(\theta)$ . In this particular tune, we opted for a fourth-order parametrization. This work, where originally eleven parameters were included in the analysis, requires a total of 2k event generations with  $\theta$  sampled across the ranges specified in Tab. III. The accuracy of the parametrization is shown in Fig. 10. This parametrization is used for the estimation of the best-fit values by minimizing the  $\chi^2$ .

### D. Discussion of data-driven priors

The basic structure of this tune is based on the model of separate nucleon and nucleus efforts. Although the emphasis here is on neutrino-nucleus parameters, some of the parameters of interest were already tuned to neutrino-nucleon data [5]. Particularly, the G18\_10a\_02\_11b tune with hydrogen and deuterium data provided with data-driven constraints for  $M_A^{\text{QEL}}$  and  $S_{\text{RES}}$  [5]. These parameters are crucial for the description of free-nucleon data and are strongly correlated with other aspects of the nuclear tune. This correlation was observed in the  $\mu\text{BooNE}$  tune, leading to best-fit results with  $M_A^{\text{QEL}} = 1.18 \pm 0.08 \text{ GeV}/c^2$  [10]. The effect of varying  $M_A^{\text{QEL}}$  on the MINERvA  $\nu_\mu\text{CC}0\pi$  prediction is shown in Fig. 11. In this work, we chose to constrain  $M_A^{\text{QEL}}$  and  $S_{\text{RES}}$  using data driven priors

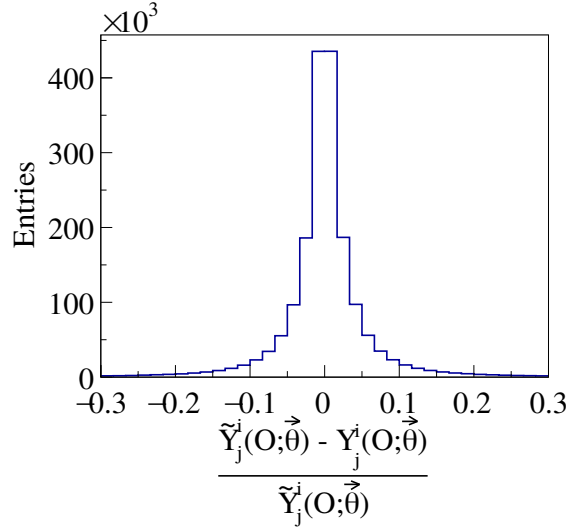


FIG. 10: Fractional difference between true MC predictions in the NS space calculated with a given  $\theta$  parameter set.

TABLE IV: Priors (a) and covariance matrix (b) for  $M_A^{\text{QEL}}$  and  $S_{\text{RES}}$  obtained to the free-nucleon tune from Ref. [5].

Parameter	Prior
$M_A^{\text{QEL}}$	$1.00 \pm 0.01 \text{ GeV}/c^2$
$S_{\text{RES}}$	$0.84 \pm 0.028$
(a)	
$M_A^{\text{QEL}}$	$S_{\text{RES}}$
$M_A^{\text{QEL}}$	$1.8 \times 10^{-4}$
$S_{\text{RES}}$	$6.0 \times 10^{-4}$
(b)	

from Ref. [5]. The information on the parameter priors central values as well as the correlation between the two parameters out of the free-nucleon tune is included in the  $\chi^2$  minimization. The complete information on the priors is provided in Tab. IV. In this analysis we also include priors on  $\omega_{\text{RPA}}$  and  $\omega_{\text{N}o\text{RPA}}$ , as discussed in Sec. III A.

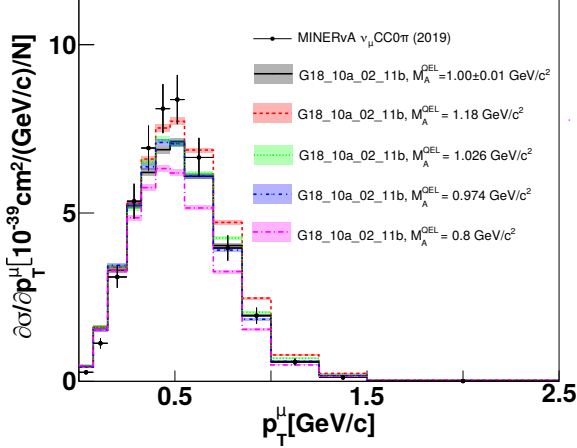


FIG. 11: Impact of  $M_A^{QEL}$  variations on MINERvA CC0 $\pi$  flux-integrated differential cross section predictions as a function of  $p_T$ . The red line corresponds to the GENIE prediction computed with the  $M_A^{QEL}$  best-fit value from the  $\mu$ BooNE tune [10]. No other parameters are modified from their nominal values.

### E. Evaluation of the $\chi^2$

The complete form for our  $\chi^2$  is:

$$\chi^2(\boldsymbol{\theta}) = \sum_i^{\mathcal{N}} \sum_{j,k}^{N_i} \sqrt{w_j^i} \Delta \tilde{Y}_j^i(\boldsymbol{\theta}) (\Sigma_{NS}^i)_{j,k}^{-1} \Delta \tilde{Y}_k^i(\boldsymbol{\theta}) \sqrt{w_k^i} + (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^T \Sigma_{\theta}^{-1} (\boldsymbol{\theta} - \boldsymbol{\theta}_0), \quad (7)$$

being  $i$  the index that runs over the  $\mathcal{N}$  datasets considered in the fit.  $\Delta \tilde{Y}_j^i$  is the difference between the NS parametrization prediction and the  $i$ th dataset at the  $j$ th bin,  $\Delta \tilde{Y}_j^i(\boldsymbol{\theta}) \equiv \tilde{Y}_j^i(\boldsymbol{\theta}) - Z_j^i$ . The  $\omega_{ij}$  is the weight applied to  $j$ th bin from the  $i$ th dataset. In this work, weights are used to include or exclude data from the analysis. In other words, they are either 1 or 0. The prediction errors,  $\delta \tilde{Y}_j^i(\boldsymbol{\theta})$ , are added in quadrature to  $\Sigma_{NS}$ . The second term takes care of correlated priors in our fit.  $\boldsymbol{\theta}_0$  and  $\Sigma_{\theta}$  are the central values vector and the covariance matrix of the priors for the parameters of interest. The details on the priors applied in this analysis are described in Sec. IV D.

## V. TUNING RESULTS

We adopt the following naming scheme to characterise each of the partial GENIE tunes presented in this work:

$$\text{Gxx[a-d]}.$$

Here

**G** is a capital letter that stands for GENIE, highlighting the authorship of the tunes.

**xx** is a number assigned to each experiment, i.e., MiniBooNE (10), T2K ND280 (20) or MINERvA (30). When using antineutrino datasets, **xx** is increased by one unit. For CCNp0 $\pi$  datasets, **xx** is increased by five units.

[a-d] refers to the alternative intranuclear hadron model used in the analysis: (a) INTRANUKE/ $hA$ , (b) INTRANUKE/ $hN$ , (c) GEANT4/Bertini and (d) INCL++.

Note that this is different from the standard naming scheme used for the tunes released through the GENIE platform. The standard naming convention from Ref. [5] will be used if one or more of the tunes produced in this work or future iterations is prepared for release in GENIE.

In total, six partial tunes are performed: three tunes on neutrino CC0 $\pi$  data, two tunes using antineutrino CC0 $\pi$  data and one tune using  $\nu_{\mu}$  CCNp0 $\pi$  data. The tunes on CC0 $\pi$  data aim to explore avenues for improving the agreement between GENIE and data, consolidate the main elements of the GENIE CC0 $\pi$  tuning methodology and provide a common ground for the discussion of tensions. The tune on CCNp0 $\pi$  data aims to highlight tensions between CC0 $\pi$  and CCNp0 $\pi$  datasets. All of the tunes presented in this work consider carbon datasets only. Joint fits to all available data will be performed at a future iteration of this work, aiming to produce the tunes that will be publicly released through the GENIE platform.

In all CC0 $\pi$  tunes, the analyses are carried out using double-differential CC0 $\pi$  data as a function of muon kinematics. Preference is given to datasets that do not require a minimum number of protons above detection threshold in the final state. Whenever CC0 $\pi$  datasets are not available for a particular experiment, the tune is performed using CC0p0 $\pi$  datasets instead.

G18\_10a\_02\_11b is the starting point for all these tunes and provides the *nominal* predictions. The corresponding names assigned to each tune prepared for the purposes of this paper are the following:

**G10a Tune** : GENIE tune to MiniBooNE  $\nu_{\mu}$  CC0 $\pi$  data [25].

**G11a Tune** : GENIE tune to MiniBooNE  $\bar{\nu}_{\mu}$  CC0 $\pi$  data [26].

**G20a Tune** : GENIE tune to T2K ND280  $\nu_{\mu}$  CC0p0 $\pi$  data [27].

**G30a Tune** : GENIE tune to MINERvA  $\nu_\mu$ CC0 $\pi$  data [28].

**G31a Tune** : GENIE tune to MINERvA  $\bar{\nu}_\mu$ CC0p0 $\pi$  data [36].

**G35a Tune** : GENIE tune to MINERvA  $\nu_\mu$ CCNp0 $\pi$  data [29].

Other measurements, including MicroBooNE ones, are used for comparisons only. Each partial tune is performed following the recipe described in Sec. IV.

### A. Discussion of partial CC0 $\pi$ tune results

Each tune's best-fit parameter values and the  $\chi^2$  calculated with the Professor parametrization at the best-fit point are summarized in Tab. V. The *nominal* and best-fit predictions are shown in Figures 12 to 18. Tab. VI provides the  $\chi^2$  values computed with each tune's GENIE prediction and corresponding dataset. In this case, the  $\chi^2$  values are calculated with the NS transformation with the GENIE predictions. Notice that the  $\chi^2$  values from Tab. VI are different to the ones provided in Tab. V. This is a consequence of the Professor parametrization not being exact.

It is observed that the description of the data after the tune improved substantially. For instance, the agreement with MINERvA  $\nu_\mu$  CC0 $\pi$  before the tune is  $\chi_{\text{Nominal}}^2 = 626/144$  DoF. After the tune,  $\chi_{\text{Nominal}}^2 = 151/144$  DoF. This is mainly a consequence of an improvement in the overall normalization for each partial tune.

All carbon tunes show similar trends; whilst the tunes are in good agreement with the priors on  $M_A^{\text{QEL}}$  and  $S_{\text{RES}}$ , the other parameters differ from the *nominal* parameter values. There is also a clear preference for QEL with RPA corrections. In addition, the tunes prefer a higher QEL, i.e.  $\omega_{\text{RPA}} + \omega_{\text{RPA}} > 1$ , and 2p2h cross section. Finally, the different tunes suggest an underlying energy dependence on the 2p2h cross section strength and shape: the G10a, G11a and G20a tunes enhance (suppress) the Valencia 2p2h cross section at the nucleon ( $\Delta$ ) region. Alternatively, the G30a and G31a tunes enhance the cross section at the nucleon and  $\Delta$  region, with  $S_{\Delta}^{2p2h} > S_N^{2p2h}$ .

The enhancement of the QEL cross section is crucial for the description of MiniBooNE CC0 $\pi$  data at  $\cos\theta_\mu < 0$ . Particularly, the G10a and G11a tunes suggest an increase of the QEL cross section of about 20%. Similar QEL scalings have been observed by MicroBooNE [10] and recent Lattice Quantum-Chromodynamics (QCD) calculations [52]. The increase (decrease) of the  $S_N^{2p2h}$  ( $S_{\Delta}^{2p2h}$  and  $S_{PL}^{2p2h}$ ) is

also crucial to correctly describe MiniBooNE  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC0 $\pi$  data.

The G20a tune also offers a better description of T2K ND280 CC0p0 $\pi$  data. This tune suggests a scaling of  $S_N^{2p2h} = 1.7 \pm 0.3$ , compatible with the results presented by MicroBooNE [10]. In this particular case, the scaling of QEL is around 10%. The post-fit value of  $\omega_{\text{NoRPA}}$ , although negative, is compatible with zero. This result is physical as  $\omega_{\text{RPA}} + \omega_{\text{NoRPA}} > 0$ , hence the total cross-section is positive. This scenario can be avoided by reducing the  $\omega_{\text{NoRPA}}$  range to [0,1.5]. However, the parameter range is not reduced further to allow a valid estimation of the error on  $\omega_{\text{NoRPA}}$ .

Before the tune, the G18\_10a\_02.11b prediction under-predicted MINERvA CC0 $\pi$  data in the phase-space regions where 2p2h events dominate ( $0.15 < p_T < 0.7$  GeV/c). The results suggest that an enhancement of QEL, as well as 2p2h, improves the agreement with data. In fact, the G30a and G31a tunes provide with a better description of  $\nu_\mu$  CC0 $\pi$  and  $\bar{\nu}_\mu$  CC0p0 $\pi$  data respectively. The improvement in the normalization of the cross section is reflected in the post-fit  $\chi^2$  values from Tab. VI. The same is true for the cross section as a function of the reconstructed neutrino energy, Fig. 18, and single-differential cross section data, Figs. 17 and 19. Both tunes over-predict the data at very low  $Q_{\text{QEL}}^2$ .

### B. Tension between CC0 $\pi$ partial tunes

Tensions between datasets can be explored by comparing the different tunes. Figure 20 compares the G10a, G20a and G30a predictions against MiniBooNE  $\nu_\mu$  CC0 $\pi$  data. Even though the normalization of the three tunes is similar, differences in the predicted cross-section shape exist. The G10a tune is the only one out of the three that successfully describes the shape of the data, as it can be seen in Fig. 20 (left). The other tunes underestimate the cross-section at backward muon angles. In addition, the G30a Tune over-predicts the cross section at forward angles as a consequence of the enhancement of the 2p2h cross section at the  $\Delta$ -region. All tunes overestimate the cross section at forward muon angles and low muon kinetic energies, as demonstrated in Fig. 20 (right).

The G31a tune is in clear tension with all the rest, including partial tunes performed with MINERvA neutrino data. In comparison with the rest of the tunes, the G31a tune prefers higher QEL and 2p2h cross sections. This leads to the over-prediction of all the other datasets. The comparison of G30a and G31a against MINERvA and MiniBooNE  $\nu_\mu$  CC0 $\pi$  data are shown in Fig. 21. The effect of this tension

TABLE V: Best-fit parameter values for the different partial tunes. Parameter values within parenthesis are kept fixed during the fit. The  $\chi^2$  values are calculated with the Professor parametrization, in accordance to Eq. 7.

Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune	G35a Tune
$M_A^{\text{QEL}}(\text{GeV}/c^2)$	$1.02 \pm 0.01$	$1.01 \pm 0.01$	$1.00 \pm 0.01$	$1.00 \pm 0.02$	$1.00 \pm 0.01$	$0.99 \pm 0.01$
$\omega_{\text{RPA}}$	$1.20 \pm 0.03$	$1.14 \pm 0.06$	$1.2 \pm 0.2$	$0.9 \pm 0.1$	$1.3 \pm 0.2$	$0.75 \pm 0.3$
$\omega_{\text{No RPA}}$	$0.05 \pm 0.02$	$0.09 \pm 0.05$	$-0.1 \pm 0.1$	$0.2 \pm 0.1$	$0.2 \pm 0.2$	$0.09 \pm 0.3$
$S_{\text{RES}}$	$0.85 \pm 0.02$	$0.86 \pm 0.05$	$0.84 \pm 0.02$	$0.84 \pm 0.03$	$0.84 \pm 0.02$	$0.84 \pm 0.02$
$S_N^{2p2h}$	$1.5 \pm 0.4$	$2.3 \pm 0.01$	$1.7 \pm 0.3$	$1.2 \pm 0.4$	$1.7 \pm 0.5$	$0.33 \pm 0.2$
$S_{\Delta}^{2p2h}$	$0.7 \pm 0.2$	$0.7 \pm 0.3$	(1.00)	$2.1 \pm 0.2$	$2.3 \pm 0.2$	$0.5 \pm 0.4$
$S_{PL}^{2p2h}$	$0.4 \pm 0.1$	$0.4 \pm 0.1$	(1.00)	$0.9 \pm 0.2$	$0.4 \pm 0.1$	$1.5 \pm 0.4$
$\chi^2$	89/130	77/71	60/55	61/137	67/53	17/19

TABLE VI: Summary of  $\chi^2$  values associated the CC0 $\pi$  datasets specified in each row. The  $\chi^2$  values are calculated using the NS method for seven different GENIE predictions: G18\_10a\_02\_11b, G10a, G11a, G20a, G30a, G31a and G35a. The values highlighted in bold correspond to the best-fit  $\chi^2$  for the partial tune predictions.

Dataset	$\chi_{\text{Nominal}}^2$	$\chi_{\text{G10a}}^2$	$\chi_{\text{G11a}}^2$	$\chi_{\text{G20a}}^2$	$\chi_{\text{G30a}}^2$	$\chi_{\text{G31a}}^2$	$\chi_{\text{G35a}}^2$	DoF
MiniBooNE $\nu_{\mu}$ CC0 $\pi$	1817	<b>121</b>	160	314	379	1279	2727	137
MiniBooNE $\bar{\nu}_{\mu}$ CC0 $\pi$	444	208	<b>214</b>	246	403	491	879	60
T2K ND280 $\nu_{\mu}$ CC0p0 $\pi$	139	447	600	<b>123</b>	237	916	239	60
MINERvA $\nu_{\mu}$ CC0 $\pi$	626	252	202	270	<b>151</b>	360	953	144
MINERvA $\bar{\nu}_{\mu}$ CC0 $\pi$	2259	1837	1680	2232	1794	<b>82</b>	1810	78

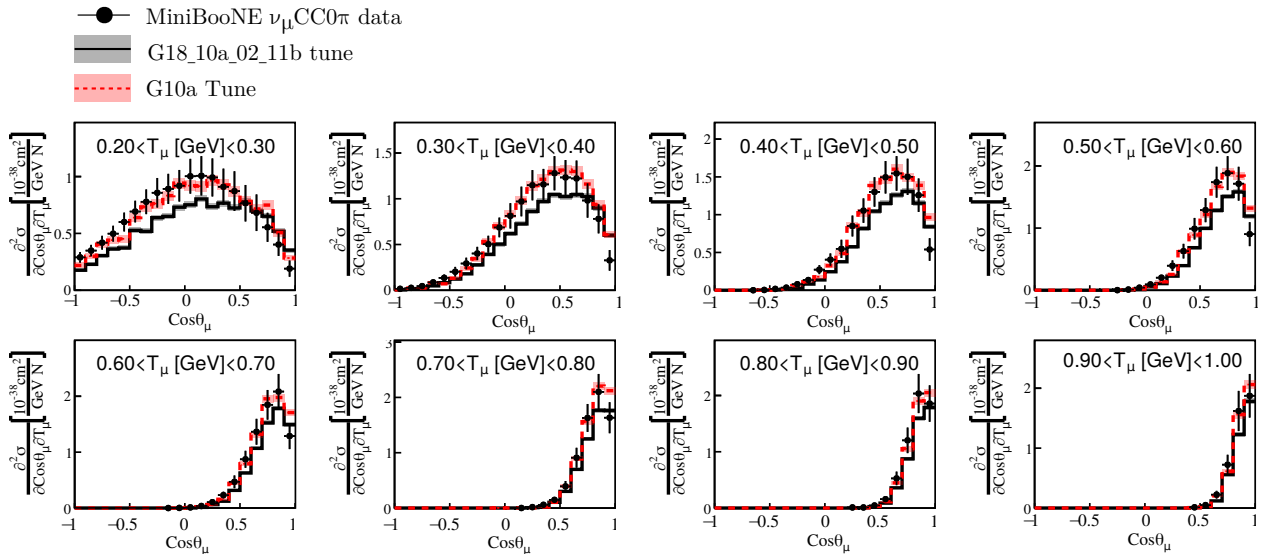


FIG. 12: Comparison of the G18\_10a\_02\_11b and G10a tunes against MiniBooNE  $\nu_{\mu}$  CC0 $\pi$  double differential data [25]. The comparisons are restricted to the  $0.2 < T_{\mu} < 1.0$  GeV phase space. The predictions are computed using the parameters specified in Tab. V. The total  $\chi^2$  associated with this dataset before and after the tune are reported in Tab. VI.



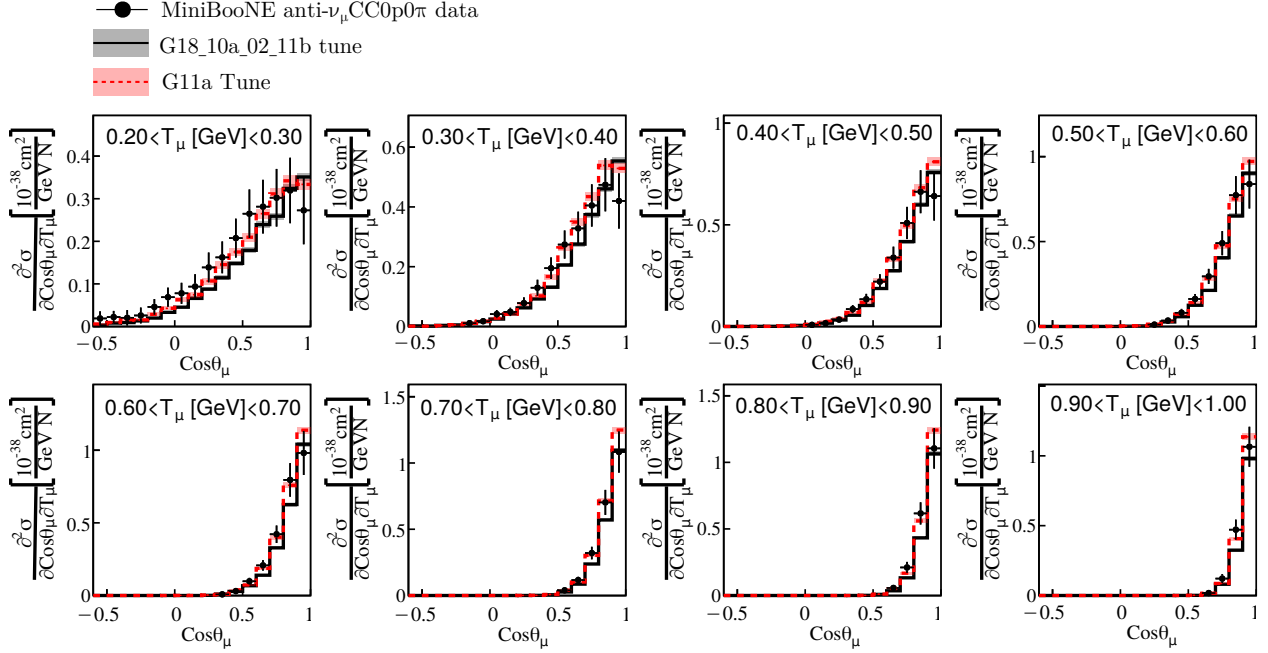


FIG. 13: Comparison of the *G18\_10a\_02\_11b* and *G11a* tunes against MiniBooNE  $\bar{\nu}_\mu$  CC0 $\pi$  double differential data [26]. The comparisons are restricted to the  $0.2 < T_\mu < 1.0$  GeV phase space. The predictions are computed using the parameters specified in Tab. V. The total  $\chi^2$  associated with this dataset before and after the tune are reported in Tab. VI.

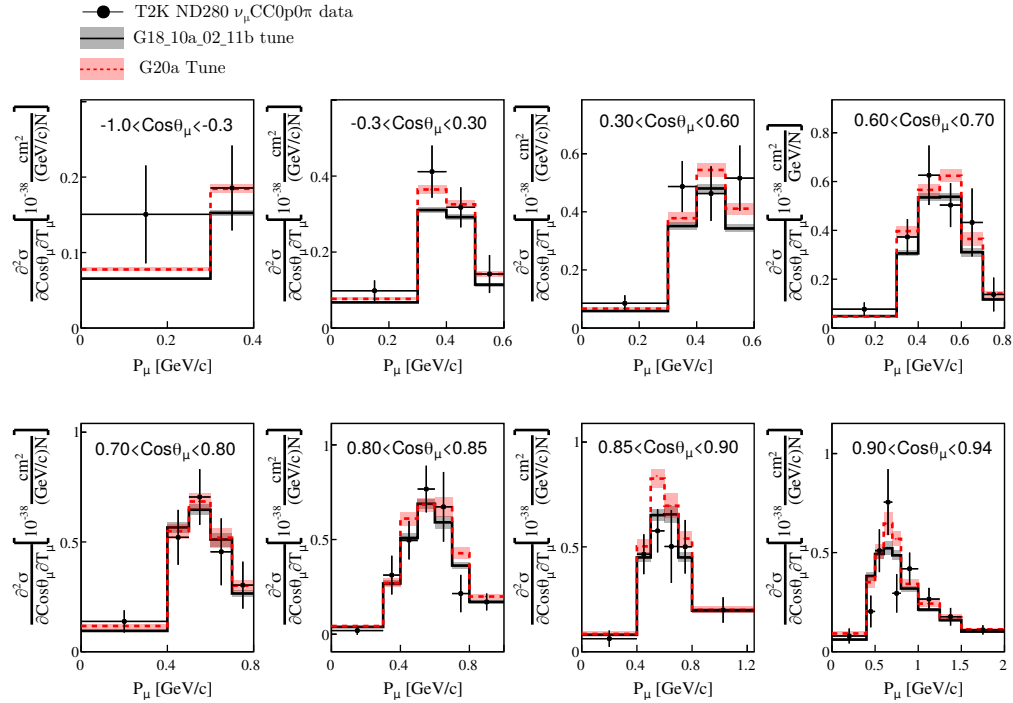


FIG. 14: Comparison of the *G18\_10a\_02\_11b* and *G20a* Tune against T2K ND280  $\nu_\mu$  CC0 $\pi$  double differential data [27]. The comparisons are restricted to the  $-1.0 < \cos\theta_\mu < 0.94$  phase space. The predictions are computed using the parameters specified in Tab. V. The total  $\chi^2$  associated with this dataset before and after the tune are reported in Tab. VI.

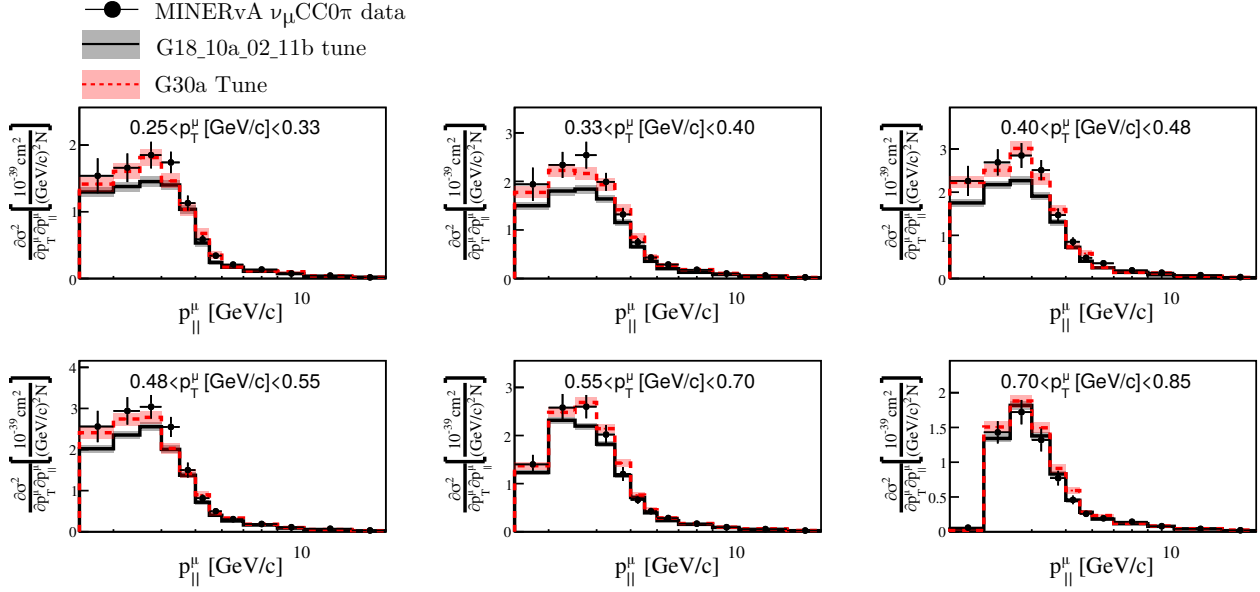


FIG. 15: Comparison of the G18\_10a\_02\_11b and G30a tunes against MINERvA  $\nu_\mu$  CC0 $\pi$  double differential data [28]. The comparisons are restricted to the  $0.25 < p_T < 0.85$  GeV/c phase space. The predictions are computed using the parameters specified in Tab. V. The total  $\chi^2$  associated with this dataset before and after the tune are reported in Tab. VI.

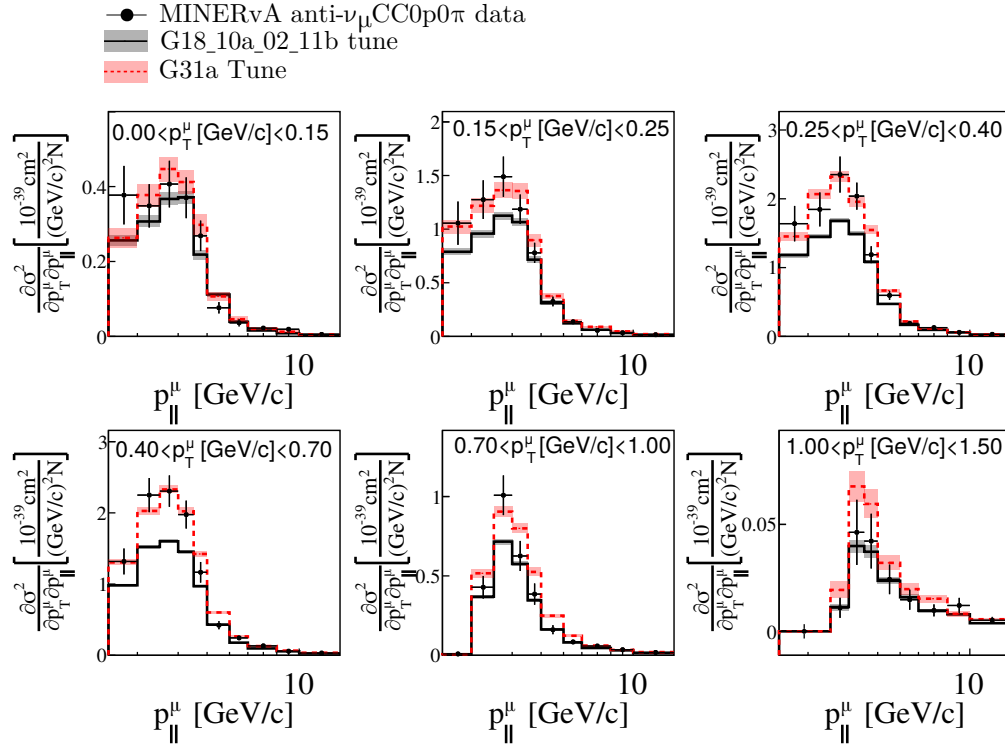


FIG. 16: Comparison of the G18\_10a\_02\_11b and G31a tunes against MINERvA  $\bar{\nu}_\mu$  CC0p0 $\pi$  double differential data [26]. The comparisons are restricted to the  $0 < p_T < 1.5$  GeV/c phase space. The predictions are computed using the parameters specified in Tab. V. The total  $\chi^2$  associated with this dataset before (after) the tune reported in Tab. VI.

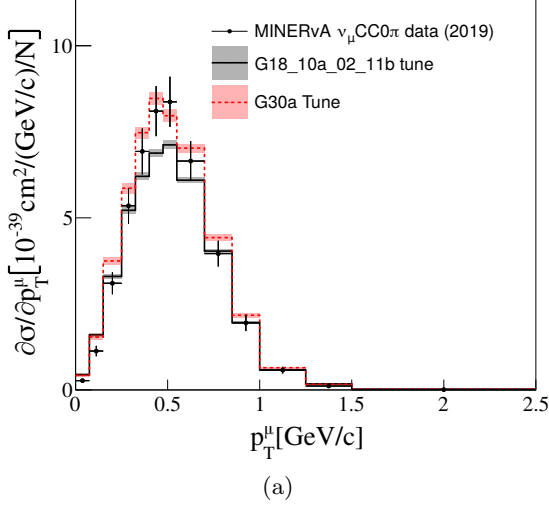


FIG. 17: Comparison of the G18\_10a\_02\_11b and G30a tunes against MINERvA  $\nu_\mu$  CC0 $\pi$  single-differential data [28]. The predictions are computed using the parameters specified in Tab. V.

on the  $\chi^2$  is reported in Tab. VI.

The tension between the G31a tune and the rest can have different origins. A possibility is that such disagreement is a consequence of the different topology definition for MINERvA's  $\bar{\nu}_\mu$  dataset, with requires no visible protons above  $T_p = 120$  MeV for the antineutrino sample. Although this tension is not observed for the T2K ND280 dataset, which requires no visible protons above 450 MeV, T2K's dataset is extracted with lower energy neutrino flux. This tension is explored further in Sec. V C.

### C. Tensions between $\nu_\mu$ CC0 $\pi$ and $\nu_\mu$ CCNp0 $\pi$ datasets

T2K ND280, MINERvA and MicroBooNE are the only experiments that released cross-section measurements for different proton multiplicities. The G18\_10a\_02\_11b, tuned to hydrogen and deuterium data, does not have good agreement with CCNp0 $\pi$  datasets.

After the partial tunes using  $\nu_\mu$  CC0 $\pi$  data, the agreement with CCNp0 $\pi$  data deteriorates. This is highlighted in Tab. VII, which summarizes the post-fit  $\chi^2$  values associated with CCNp0 $\pi$  datasets. In all cases, the  $\chi^2$  computed with each partial tune prediction increases with respect to the  $\chi^2$  computed with the *nominal* G18\_10a\_02\_11b tune.

All G10a, G20a and G30a tunes overpredict  $\nu_\mu$  CCNp0 $\pi$  data. Figure 22 shows a comparison of the partial tune predictions against different single-differential CCNp0 $\pi$  cross-section measure-

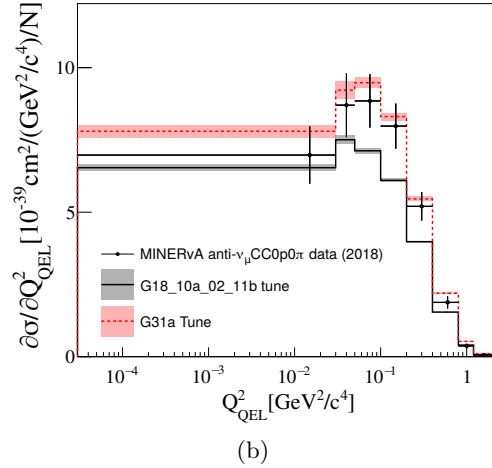
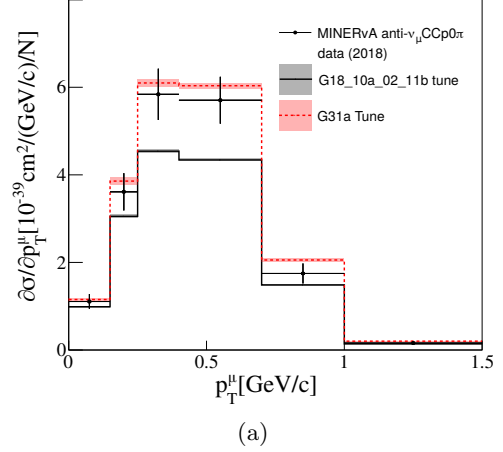


FIG. 18: Comparison of the G18\_10a\_02\_11b and G31a tunes against MINERvA  $\bar{\nu}_\mu$  CC0p0 $\pi$  single-differential data [26]. The predictions are computed using the parameters specified in Tab. V.

ments from MINERvA. Figure 22 shows that none of the available tunes can describe the peak at low  $\delta p_T$  and that all partial tunes overestimate the cross section at low proton momentum and forward angles. The same observations are made when comparing the tunes against T2K ND280 and MicroBooNE CCNp0 $\pi$  data, see Figs. 23 and 24, respectively.

To further explore this tension, an additional tune is performed using the MINERvA  $\nu_\mu$  CCNp0 $\pi$  dataset as a function of the proton angle. Following the naming scheme described at the beginning of Sec. V, this tune is referred to as G35a. The best-fit results are listed in Tab. V.

The G35a tune suggests a significant reduction of the QEL cross section. In addition, the tune suppresses the Valencia cross-section peak prediction at  $W = M_N$  and shifts the  $\Delta$  peak to  $W > M_\Delta$ . This result contradicts the rest of the partial tunes presented in this article, reinforcing the fact that

TABLE VII: Summary of  $\chi^2$  values associated the CCNp0 $\pi$  datasets specified in each row. The  $\chi^2$  values are calculated using the NS method for seven different tunes: **G18\_10a\_02\_11b**, **G10a**, **G11a**, **G20a**, **G30a** and **G31a**. The values highlighted in bold correspond to the best-fit  $\chi^2_{\text{G35a}}$  for the partial tune using the specified dataset.

Dataset	$\chi^2_{\text{Nominal}}$	$\chi^2_{\text{G10a}}$	$\chi^2_{\text{G11a}}$	$\chi^2_{\text{G20a}}$	$\chi^2_{\text{G30a}}$	$\chi^2_{\text{G31a}}$	$\chi^2_{\text{G35a}}$	DoF
T2K ND280 CCNp0 $\pi$ data								
$d\sigma/d\delta p_T$	228	1741	1499	883	759	95	25	8
$d\sigma/d\delta\phi_T$	292	2489	2117	1190	1049	1950	16	8
$d\sigma/d\delta\alpha_T$	27	58	53	42	41	95	21	8
MINERvA CCNp0 $\pi$ data								
$d\sigma/dp_p$	21	22	25	32	36	58	27	25
$d\sigma/d\theta_p$	58	153	150	113	129	226	<b>20</b>	26
$d\sigma/d\delta p_T$	102	637	568	360	352	625	42	24
$d\sigma/d\delta\phi_T$	87	505	467	314	354	566	18	23
$d\sigma/d\delta\alpha_T$	15	21	29	24	30	57	17	12
$d\sigma/d\delta p_{Tx}$	159	727	710	467	555	768	62	32
$d\sigma/d\delta p_{Ty}$	127	832	776	553	599	792	51	33
MicroBooNE CCNp0 $\pi$ data								
$d\sigma/dp_p^{\text{reco}}$	71	402	413	245	251	1186	40	10
$d\sigma/d\cos\theta_p^{\text{reco}}$	413	238	236	210	245	471	149	12
$d\sigma/dp_p^{\text{reco}}$	33	96	97	73	76	267	20	10
$d\sigma/d\cos\theta_p^{\text{reco}}$	100	176	179	135	139	393	33	9
$d\sigma/d\theta_{\mu p}^{\text{reco}}$	549	186	196	199	218	304	136	6

there is a strong tension between CC0 $\pi$  and CCNp0 $\pi$  datasets. The summary of  $\chi^2$  is reported in Tab. VI and Tab. VII.

An important observation is that the **G35a** tune also improves the agreement with MicroBooNE CCNp0 $\pi$  data, suggesting that a possible A-dependency on the parameters does not play an important role.

The tension between CC0 $\pi$  and CCNp0 $\pi$  datasets needs to be resolved before attempting a global tune of CC0 $\pi$  data that can describe all data available to date. Some modelling aspects that may contribute to this tension are investigated in Sec. VI.

## VI. INVESTIGATION OF TENSIONS BETWEEN CC0 $\pi$ AND CCNP0 $\pi$ DATASETS

This section offers an insight into possible modeling implementations that may contribute to the tension between CC0 $\pi$  and CCNp0 $\pi$  datasets and explores avenues of accommodating both within future joint tunes. None of the uncertainties described in this section has a big impact on CC0 $\pi$  datasets.

### 1. Nuclear model variations

The nuclear model determines the momentum and binding energy of the hit nucleon. In GENIE, three nuclear models are available: Relativistic Fermi Gas (RFG), Local Fermi Gas (LFG) and Correlated Fermi Gas (CFG) [14]. By default, **G18\_10a\_02\_11b** uses the LFG.

The nuclear model choice affects the CCNp0 $\pi$  predictions. Figure 25 shows the impact of the underlying nuclear model against CCNp0 $\pi$  single-differential cross-section measurements as a function of  $\delta p_T$ . Differences between the models are significant for the cross-section peak prediction at low  $p_T$ . The RFG model is the only one out of the three that predicts the MINERvA data below the maximum. However, it still over-predicts the cross section at the peak. Alternatively, the CFG model successfully predicts the peak normalization. This is reflected in the  $\chi^2_{\text{CFG}}$ , reported in Tab. VIII.

The main characteristic of the RFG and the CFG implementations in GENIE is that nucleons can have a momentum above the Fermi momentum in its ground state. This tail in the momentum distri-

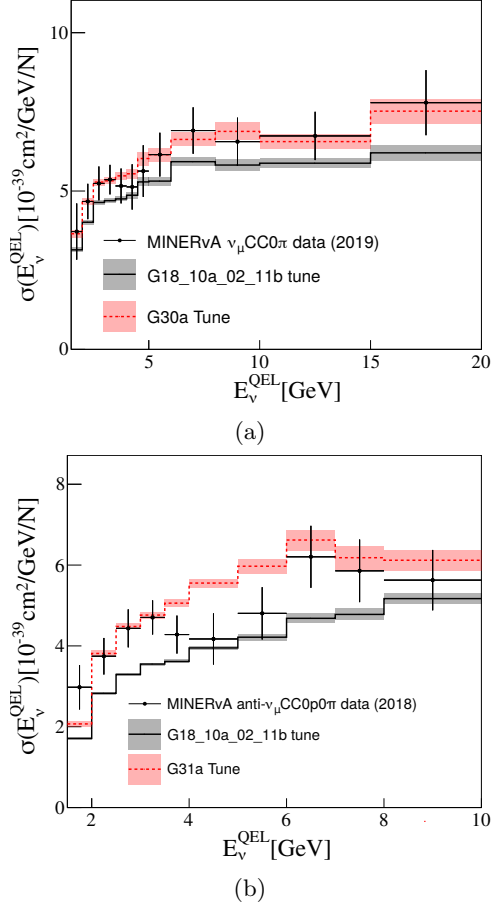


FIG. 19: Comparison of G18\_10a\_02\_11b, G31a (a) and G31a (b) against MINERvA  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC0p0 $\pi$  integrated cross section data [26, 28]. The predictions are computed using the parameters specified in Tab. V.

bution is a consequence of nucleon correlations in the nuclear medium. As a consequence of including those effects in the nuclear model, the description of the tail of the  $\delta p_T$  distribution improves. This study suggests that using a more elaborate nuclear model is key to describe CCNp0 $\pi$  measurements.

The differences between the three GENIE nuclear model predictions are not enough to explain the discrepancy between CC0p0 $\pi$  and CCNp0 $\pi$  data: all models predict a higher cross section for processes with protons in the final state concerning those with no protons in the final state. This is highlighted in Fig. 26.

## 2. Nucleon Final State Interaction model variations

Mismodeling of nucleon FSI can cause migration between CC0p0 $\pi$  and CCNp0 $\pi$  samples [53].

TABLE VIII: Summary of  $\chi^2$  values associated with the CCNp0 $\pi$  datasets specified in each row. The  $\chi^2$  values are calculated using the NS method for three GENIE predictions. The GENIE predictions are calculated with the G18\_10a\_02\_11b tune. Each prediction uses a different nuclear model: RFG, LFG or CFG.

G18_10a_02_11b				
Dataset	$\chi_{LFG}^2$	$\chi_{RFG}^2$	$\chi_{CFG}^2$	DoF
T2K ND280 CCNp0 $\pi$ data				
$d\sigma/d\delta p_T$	228	149	27	8
$d\sigma/d\delta\phi_T$	292	29	20	8
$d\sigma/d\delta\alpha_T$	27	25	26	8
MINERvA CCNp0 $\pi$ data				
$d\sigma/dp_p$	21	23	15	25
$d\sigma/d\theta_p$	58	35	34	26
$d\sigma/d\delta p_T$	102	95	31	24
$d\sigma/d\delta\phi_T$	87	32	18	23
$d\sigma/d\delta\alpha_T$	15	17	14	12
$d\sigma/d\delta p_{Tx}$	159	61	48	32
$d\sigma/d\delta p_{Ty}$	127	40	42	33
MicroBooNE CCNp0 $\pi$ data				
$d\sigma/dp_\mu^{\text{reco}}$	71	35	32	10
$d\sigma/d\cos\theta_\mu^{\text{reco}}$	413	137	123	12
$d\sigma/dp_p^{\text{reco}}$	33	25	27	10
$d\sigma/d\cos\theta_p^{\text{reco}}$	100	49	42	9
$d\sigma/d\theta_{\mu p}^{\text{reco}}$	549	195	155	6

Ref. [54] suggests increasing the nucleon mean-free path in cascade models might improve the agreement with CCNp0 $\pi$  data from T2K ND280 and MINERvA. This possibility is explored here. The effect of the mean-free path implementation is validated against carbon transparency data.

A crucial test for FSI models is to be able to reproduce nuclear transparency data from electron scattering experiments. Transparency is defined as the probability for the knocked-out nucleon to not undergo FSIs in the nuclear environment and it can be measured using electrons or neutrinos. In transparency measurements, the final-state nucleon is produced inside the nucleus. This feature is common with neutrino experiments, making transparency data extremely valuable to characterize and test FSI modeling uncertainties. Unfortunately, nuclear transparency measurements are scarce. Few data points on proton transparency on carbon as a function of the proton momentum are available in

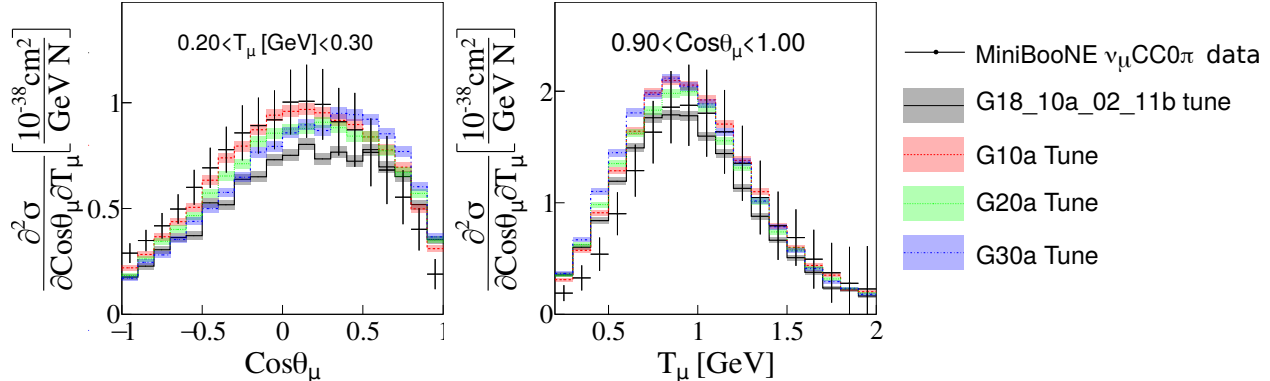


FIG. 20: Comparison of the G18\_10a\_02\_11b, G10a, G20a and G30a tunes against MiniBooNE  $\nu_\mu$  CC0 $\pi$  integrated cross-section data [25]. The predictions are computed using the parameters specified in Tab. V.

Ref. [55–58].

Transparency can be easily calculated within MC event generators as a ratio between the distribution of final-state protons which did or did not rescatter while leaving the nuclear environment. Ref. [53] provided the first direct comparison of transparency calculations using a neutrino event generator. This analysis took into account the experimental acceptances of the electron scattering experiments in the transparency definition. Such an analysis could be replicated in GENIE; however, it is out of the scope of the present work. To be able to compare GENIE’s transparency calculations with data, we scale the GENIE predictions by the ratio between the transparency prediction from Ref. [53] with and without acceptance cuts. This approach was used in Ref. [46].

The impact on the T2K ND280 cross section of variations in the nucleon mean-free path is shown in Fig. 27 as a function of proton multiplicity. It is observed that a higher nucleon mean-free path results in an increase of the proton multiplicity. An interesting observation is that, when reducing the mean-free path, a higher cross-section is predicted for events with no protons above detection threshold, indicating a reduction of the mean-free path could be key to resolving the tension between CC0 $\pi$  and CCN $\pi$  datasets.

The effect on carbon transparency calculations is shown in Fig. 28. The red and blue bands show the effect on the predictions when scaling up and down the nucleon mean-free path by 10% and 30% respectively. The 10% variation describes the data points with proton kinetic energies above 600 MeV within the  $1\sigma$  error bound. The 30% variation covers all the data available.

Ref. [46] compares the different FSI models implemented in MC event generators. These differ

mainly in the implementation of nuclear effects, such as Pauli Blocking and nucleon-nucleon correlations, in FSI codes. They observed that at high kinetic energies, differences between the calculations do not play a major role. However, for  $T_p < 200$  MeV, the spread between the different transparency calculations is significant, indicating stronger model dependence at low proton kinetic energies.

The T2K ND280 and MINERvA  $\nu_\mu$  CCN $\pi$  measurements require at least one proton above the detection threshold of  $p_p \sim 500$  MeV/c. Therefore, FSI modeling uncertainties, which affect transparency calculations at low energies, are not expected to have a big impact on MINERvA and T2K ND280 CCN $\pi$  measurements. These could affect MINERvA  $\bar{\nu}_\mu$  CC0 $\pi$  measurements, which require no protons with momentum above 120 MeV/c. However, variations of the mean-free path have a small effect on MINERvA  $\bar{\nu}_\mu$  CC0 $\pi$  predictions.

The  $hA$  and  $hN$  FSI models are build on a simplistic view of the nuclear environment. More complex approaches offer an improved description of CCN $\pi$  [27, 59, 60]. Another possible line of study would be to determine whether more elaborate FSI models can resolve the tension. Such a study is out of the scope of this paper but will be explored in future iterations of this work.

## VII. CONCLUSIONS

This article describes the first neutrino-nucleus cross-section tuning effort within the GENIE Collaboration. The goal of this work is to tune GENIE against CC0 $\pi$  data and quantify the major sources of CC0 $\pi$  modelling uncertainties. In total, five partial tunes using double-differential flux-integrated  $\nu_\mu$  or  $\bar{\nu}_\mu$  CC0 $\pi$  cross-section measurements on carbon as

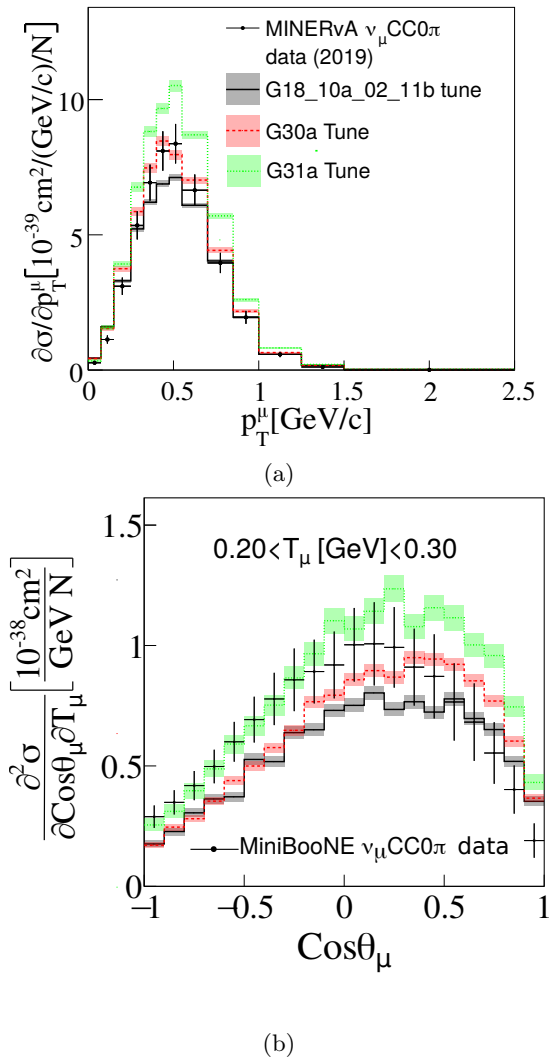


FIG. 21: Comparison of the G18\_10a\_02\_11b, G30a and G31a tunes against (a) MINERvA [28] and (b) MiniBooNE [25]  $\nu_\mu \text{CC}0\pi$  double-differential cross-section data. The predictions are computed using the parameters specified in Tab. V.

a function of the outgoing muon kinematics. Each tune is performed with data from either MiniBooNE, T2K ND280 or MINERvA following the same analysis procedure. Even though these experiments all use carbon as target, they are exposed to different neutrino beams, which peak at a different energy: the MiniBooNE and T2K fluxes peak below 1 GeV, whereas the MINERvA flux peaks at 3 GeV. Hence, this work exploits tuning to study possible energy dependencies of components of the  $\text{CC}0\pi$  cross section by comparing each of the partial tune results. This analysis is based on the G18\_10a\_02\_11b CMC, which was previously tuned against free nucleon data [5].

This tune confronted a number of new challenges with respect to previous GENIE free nucleon tuning efforts. This led to important changes in the GENIE tuning software. In particular, modern nuclear data provide the full correlation between the data release bins due to systematic uncertainties. In order to incorporate this information in the analysis, the definition of the  $\chi^2$  is modified to avoid the Peele's Pertinent Puzzle, which leads to nonphysical normalization factors.

This analysis considers a total of seven parameters which attempt to capture the basic features of the component interactions - QEL, 2p2h, and RES as implemented in the G18\_10a\_02\_11b model set. Some of the parameters used in this work affect the simulation of neutrino interactions on free nucleon. We chose to constrain these parameters with correlated priors coming from previous GENIE tunes to bubble chamber data [5]. In addition, new parametrizations that encapsulate possible nuclear uncertainties were developed, using the Valencia model [13] for the QEL and 2p2h processes as a basis for choosing parameters. These affect the strength of the RPA correction for CCQEL calculations in a nuclear environment as well as the strength and shape of the 2p2h cross section - these are the main topic of this work. Other relevant  $\text{CC}0\pi$  parameterizations that affect the nuclear or FSI models are discussed. These are found to be highly correlated with other aspects of the tune or not too sensitive to the  $\text{CC}0\pi$  data considered in the tune. For these reasons, these are not included in the tunes presented here.

All tunes present a common trend: the QEL and 2p2h cross sections are enhanced and there is a preference for the QEL cross section with RPA corrections. In addition, the tune results are in agreement with the priors imposed on free nucleon parameters. Despite similarities, a clear energy dependence is observed for the 2p2h cross-section shape: the MiniBooNE and T2K tunes enhance the 2p2h cross section at the nucleon region,  $W = M_N$ , while suppressing it at the  $\Delta$  region,  $W = M_\Delta$ . Alternatively, both MINERvA tunes enhance the cross section in both regions, with an even higher scaling factor at the  $\Delta$  region. This suggests a dependence of the  $\text{CC}0\pi$  cross section on the neutrino energy which is manifested in this work as a change in the shape and strength of the 2p2h cross section.

Tensions between the various  $\text{CC}0\pi$  partial tunes and existing  $\text{CCNp}0\pi$  data from T2K ND280, MINERvA and MicroBooNE exist. These results were shown in Table VI and are a key result of this work. Parameters that give good agreement with one data set give poor  $\chi^2$  values for the other data sets. Since MiniBooNE and T2K are at very similar neutrino,

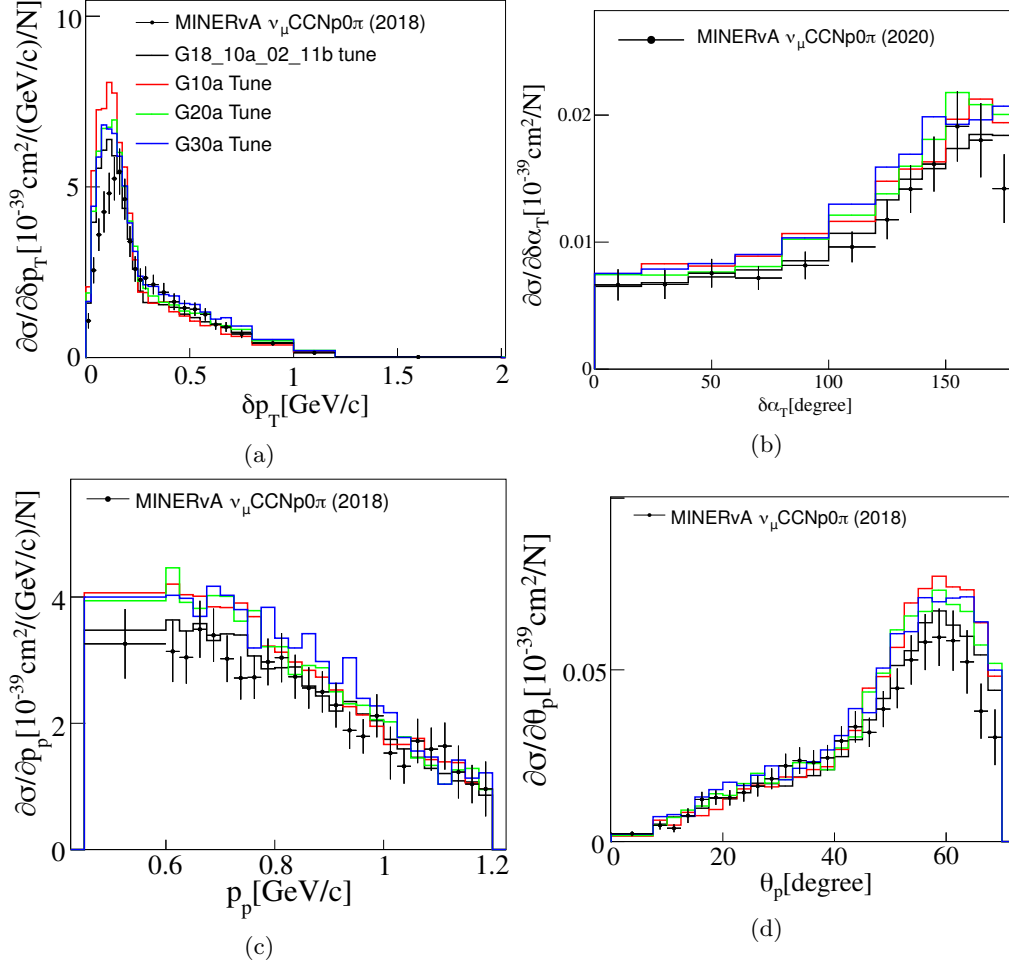


FIG. 22: Comparison of the G18\_10a\_02\_11b, G10a, G20a and G30a tunes against MINERvA  $\nu_\mu$  CCNp0 $\pi$  single-differential cross-section data as a function of (a)  $\delta p_T$ , (b)  $\alpha_T$ , (c)  $p_p$  or (d)  $\theta_p$ . In order to ease the readability of these plots, no statistical errors are shown. The predictions are computed using the parameters specified in Tab. V.

this indicates tensions between the data sets of the two experiments. In all cases, the tunes over-predict CCNp0 $\pi$  data. This tension was further investigated with a dedicated tune, which is performed using MINERvA  $\nu_\mu$  CCNp0 $\pi$  data. The result suggests that a reduction of the QEL and 2p2h cross sections would improve the agreement with all CCNp0 $\pi$  data, contradicting the CC0 $\pi$  partial tunes. This tune also improves the agreement with MicroBooNE CCNp0 $\pi$  data, suggesting that a possible  $A$ -dependence on the tune parameters is small, as was indicated in the MicroBooNE tune [10]. The disagreement with CCNp0 $\pi$  data is further explored in this paper, highlighting the importance of using a more realistic nuclear model and possible changes to FSI models to describe existing CCNp0 $\pi$  data. The tension observed between CC0 $\pi$  and CCNp0 $\pi$  datasets must be addressed before attempting to perform a global

tune with all the available data.

## VIII. ACKNOWLEDGEMENTS

We would like to thank Andy Buckley (University of Glasgow, UK) and Holger Schultz (Institute of Particle Physics Phenomenology, University of Durham, UK) for their support interfacing the Professor tool with the software products that underpin the GENIE global analyses. We would like to thank the CC-IN2P3 Computing Center, as well as the Particle Physics Department at Rutherford Appleton Laboratory for providing computing resources and for their support. This work, as well as the ongoing development of several other GENIE physics tunes was enabled through a PhD studentship funded by STFC through LIV.DAT, the



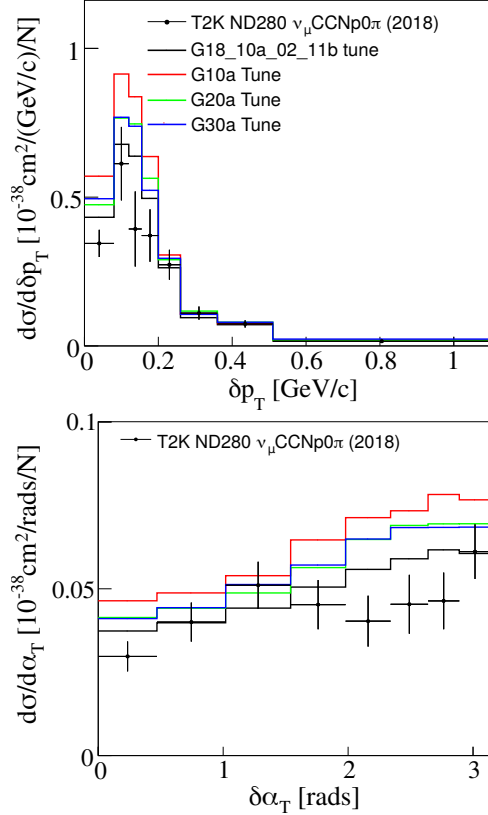


FIG. 23: Comparison of the G18\_10a\_02\_11b, G10a, G20a and G30a tunes against T2K ND280  $\nu_\mu$  CCNp0 $\pi$  single-differential cross-section data as a function of (a)  $\delta p_T$  or (b)  $\delta \alpha_T$  [27]. In order to ease the readability of these plots, no statistical errors are shown. The predictions are computed using the parameters specified in Tab. V.

Liverpool Big Data Science Centre for Doctoral Training (project reference: 2021488). The initial conceptual and prototyping work for the development of the GENIE / Professor interfaces, as well as for the development of the GENIE global analyses framework that, currently, underpins several analyses, was supported in part through an Associateship Award by the Institute of Particle Physics Phenomenology, University of Durham. We thank: Stephen Dolan and Jaafar Chakrani for providing the method to correct for Peelle’s Persistent Paradox; Daniel Ruterbories and Stephen Dolan for guidance to implement MINERvA’s and T2K’s analysis requirements in GENIE Comparisons; Xianguo Lu for discussion and comments on the paper.

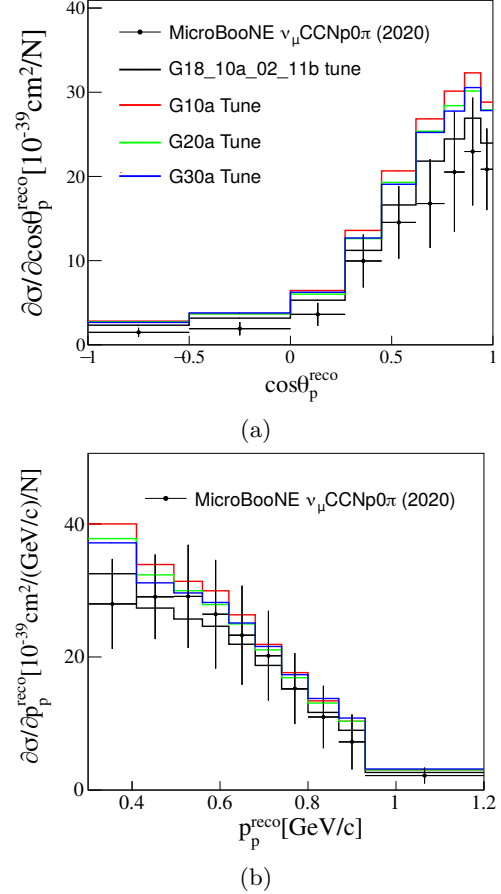


FIG. 24: Comparison of the G18\_10a\_02\_11b, G10a, G20a and G30a tunes against MicroBooNE  $\nu_\mu$  CCNp0 $\pi$  single-differential cross-section data as a function of (a)  $\cos \theta_p^{\text{reco}}$  or (b)  $p_p^{\text{reco}}$  [35]. In order to ease the readability of these plots, no statistical errors are shown. The predictions are computed using the parameters specified in Tab. V.

## Appendix A: Kinematic quantities of interest for CC0 $\pi$ measurements

Differential neutrino cross-section measurements are given as a function of different kinematic quantities. In this paper, these kinematic quantities are classified into *direct*, *inferred with an underlying process hypothesis* or *inferred without an underlying process hypothesis*.

### 1. Direct

Kinematic quantities that can be measured by the detector are classified as *direct*. For instance, an example of *direct* quantity would be the muon momentum,  $p_\mu$ , or angle with respect to the beam-line

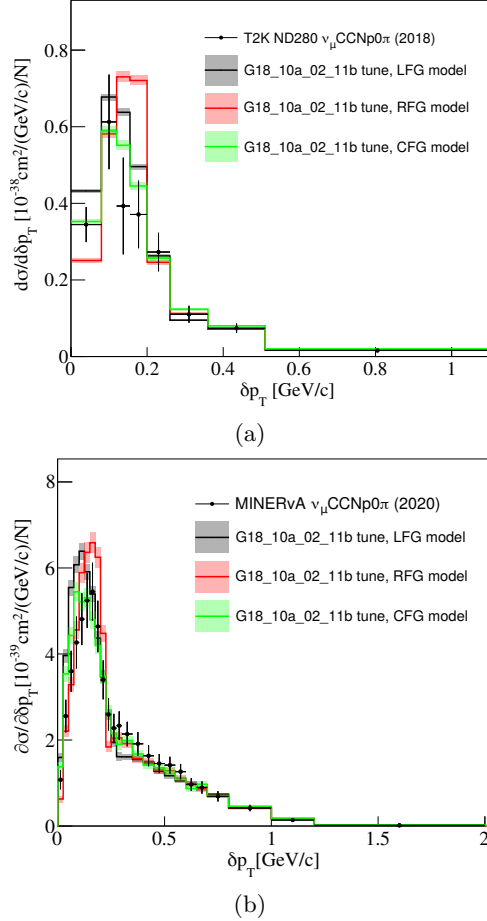


FIG. 25: Comparison of the G18\_10a\_02\_11b tune against T2K ND280 [27] (a) and MINERvA [30] (b)  $\nu_\mu$  CCNp0 $\pi$  single-differential cross-section data as a function of  $\delta\alpha_T$ . Three calculations are shown for different nuclear models: LFG (black), RFG (red) and CFG (green). The errors correspond to statistical uncertainties only.

axis,  $\theta_\mu$ . In some cases, the muon kinetic energy,  $T_\mu$ , is used instead. All cross-section measurements specified in Tab. II released data as a function of the muon kinematics. Depending on the detector capabilities, *direct* quantities can also be related to proton kinematics. We refer to proton momentum and angle as  $p_p$  and  $\theta_p$  respectively.

Muon *direct* quantities depend strongly on the neutrino energy and these are less sensitive to nuclear effects. This motivated the recent efforts on the study of more exclusive topologies that allow measurement of the cross section as a function of the outgoing-proton kinematics [27, 29, 31, 32]. These depend weakly on the neutrino energy and are significantly altered by nuclear effects [37].

In some cases, the differential cross-section mea-

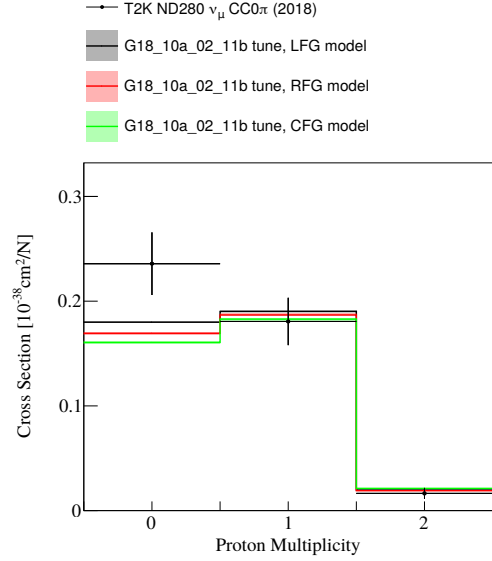


FIG. 26: Comparison of G18\_10a\_02\_11b against T2K ND280  $\nu_\mu$  CCNp0 $\pi$  total cross section data as a function of the proton multiplicity [27]. Three calculations are shown for different nuclear models: LFG (black), RFG (red) and CFG (green).

surements are presented as a function of the reconstructed *direct* quantities. Kinematic quantities in the reconstructed space are denoted with a 'reco' superscript. For instance,  $p_\mu^{\text{reco}}$  stands for reconstructed muon momentum.

## 2. Inferred kinematic with an underlying process hypothesis

This category includes measurements that rely on the reconstruction of neutrino properties assuming a specific interaction type. For instance, the kinematics of a CC0 $\pi$  event can be reconstructed under the hypothesis that the initial nucleon was at rest and that there is no inelastic production of mesons in the final state (QEL hypothesis). Under this hypothesis, the reconstructed neutrino energy ( $E_\nu^{\text{QEL}}$ ) and squared four-momentum transferred ( $Q_{\text{QEL}}^2$ ) are:

$$E_\nu^{\text{QEL}} = \frac{M_f^2 - (M_i - E_b)^2 - M_\mu^2 + 2(M_i - E_b)E_\mu}{2(M_i - E_b - E_\mu + p_\mu \cos \theta_\mu)} \quad (\text{A1})$$

$$Q_{\text{QEL}}^2 = 2E_{\nu,\text{QEL}}(E_\mu - p_\mu \cos \theta_\mu) - M_\mu^2 \quad (\text{A2})$$

where  $M_i$  ( $M_f$ ) is the initial (final) nucleon mass,  $M_\mu$  is the muon mass, and  $E_\mu$  is the muon energy. For the neutrino analysis,  $M_i = M_n$  and  $M_f = M_p$ , whereas  $M_i = M_p$  and  $M_f = M_n$  for the antineutrino case. The binding energy,  $E_b$ , depends on the

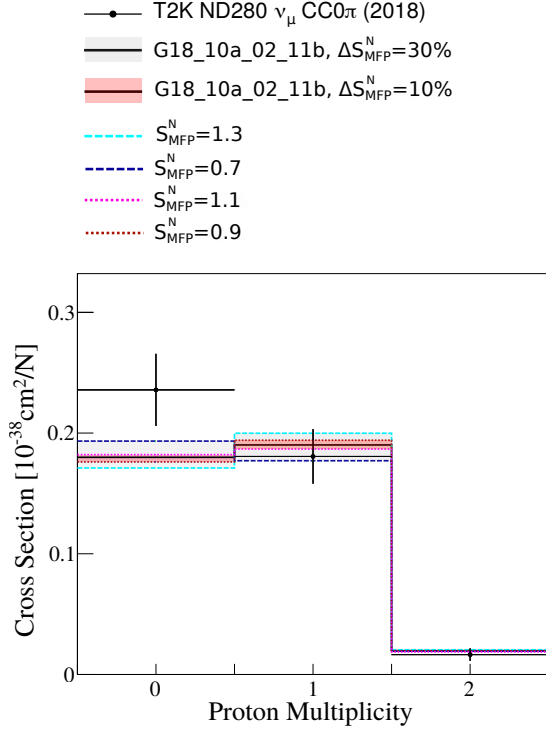


FIG. 27: Comparison of the G18\_10a\_02\_11b tune against T2K ND280  $\nu_\mu$  CCNp0 $\pi$  total cross-section data as a function of the proton multiplicity. The GENIE prediction (black) is calculated using the G18\_10a\_02\_11b. The error bands correspond to the expected uncertainty when varying the nucleon mean free path by 10% (red) and 30% (grey).

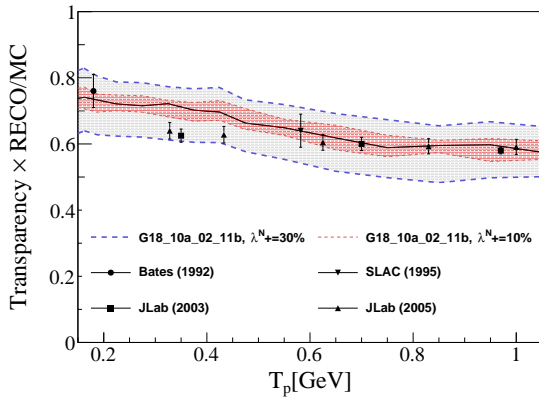


FIG. 28: Comparison of proton transparency in carbon against the available electron scattering data [55–58]. The GENIE prediction (black) is calculated using the G18\_10a\_02\_11b. The error bands correspond to the expected uncertainty when varying the nucleon mean free path by 10% (red) and 30% (grey). The predictions have been corrected according to experiments acceptance effects as determined in Ref. [53].

target type. Its specific value is provided in each analysis.

The main disadvantage of using these quantities is that the underlying hypothesis is uncertain. The presence of the nuclear environment complicates the characterization of event topologies: no single-event topology is produced only by a single underlying process. This is highlighted by the T2K ND280 results on inferred kinematics [27]. In their analysis, they reconstruct the energy and momentum of the outgoing proton assuming a QEL interaction. Instead of presenting the cross-section measurement as a function of the *inferred with kinematic with an underlying process* quantities, they used the difference between the *direct* and the *inferred* one. In particular, T2K ND280 explored this quantity for the proton kinematics:

$$\begin{aligned}\Delta p_p &\equiv |\mathbf{p}_p^{\text{direct}}| - |\mathbf{p}_p^{\text{QEL}}|, \\ \Delta \theta_p &\equiv |\theta_p^{\text{direct}}| - |\theta_p^{\text{QEL}}|, \\ |\Delta \mathbf{p}_p| &\equiv |\mathbf{p}_p^{\text{direct}} - \mathbf{p}_p^{\text{QEL}}|.\end{aligned}\quad (\text{A3})$$

These are referred to as *proton inferred kinematics* quantities. Here, the superscript indicates whether the kinematic quantity is *direct* (i.e.  $\mathbf{p}_p^{\text{direct}}$ ) or *inferred* (i.e.  $\mathbf{p}_p^{\text{QEL}}$ ). The reconstructed proton energy and momentum under the QEL hypothesis are:

$$\begin{aligned}E_p^{\text{QEL}} &= E_\nu^{\text{QEL}} - E_\mu + M_p \\ \mathbf{p}_p^{\text{QEL}} &= (-p_\mu^x, -p_\mu^y, -p_\mu^z + E_\nu^{\text{QEL}})\end{aligned}$$

These kinematic quantities can be used to highlight nuclear effects in CC0 $\pi$  measurements, as the quantities defined in Eq. A3 deviate from zero when nuclear effects are present.

### 3. Inferred without an underlying process hypothesis

This category includes those kinematical quantities which are inferred from *direct* ones but do not assume a specific underlying interaction process. An example of interest for this work is the Single-Transverse Kinematic Imbalance (STKI) variables [37]. STKI provide direct constraints on nuclear effects that, in some cases, have a weak dependence on the neutrino energy. STKI quantities are inferred from the muon and primary state hadron kinematics and only detectors capable of measuring low energy hadrons can provide such information. So far, only T2K ND280 and MINERvA have released single-differential flux-integrated cross-section measurements as a function of these quantities [27, 29, 30].

The *transverse momentum imbalance*,  $\delta\mathbf{p}_T$ , is defined as the sum of the transverse muon and proton momentum:

$$\delta\mathbf{p}_T \equiv \mathbf{p}_T^\mu + \mathbf{p}_T^p.$$

As the neutrino travels in the longitudinal direction, the transverse muon momentum is related to the transverse momentum transfer as  $\mathbf{p}_T^\mu = -\mathbf{q}_T$ . The angle between  $\delta\mathbf{p}_T$  and  $-\mathbf{p}_T^\mu$  is known as *boosting angle*,  $\delta\alpha_T$ :

$$\delta\alpha_T \equiv \arccos\left(\frac{-\mathbf{p}_T^\mu \cdot \delta\mathbf{p}_T}{p_T^\mu \delta p_T}\right).$$

The deflection of the nucleon with respect to  $\mathbf{q}_T$  is measured with the  $\delta\phi_T$  angle:

$$\delta\phi_T \equiv \arccos\left(\frac{-\mathbf{p}_T^\mu \cdot \mathbf{p}_T^p}{p_T^\mu p_T^p}\right).$$

A more recent study investigates the CC0 $\pi$  cross-section dependency on the muon-proton momentum imbalances parallel ( $\delta p_{Ty}$ ) and longitudinal ( $\delta p_{Tx}$ ) to the momentum transfer in the transverse plane [30]. These quantities are mathematically defined as:

$$\begin{aligned} \delta p_{Tx} &= (\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_T^\mu) \cdot \delta\mathbf{p}_T \\ \delta p_{Ty} &= -\hat{\mathbf{p}}_T^\mu \cdot \delta\mathbf{p}_T \end{aligned}$$

given the Cartesian coordinate system defined with respect to the neutrino and muon kinematics. The neutrino direction is given by  $\hat{\mathbf{p}}_\nu$ . All these quantities define what experiments refer to as STKI variables.

A graphical representation of the definition of the STKI variables for a neutrino interaction with and without nuclear effects is shown in Fig. 30. When the interaction occurs with a static free nucleon, i.e. no nuclear effects,  $\mathbf{p}_T^\mu = -\mathbf{p}_T^p$ ,  $\delta\mathbf{p}_T = 0$  and  $\delta\phi_T = 0$ , see Fig. 29a. However, this picture is modified by Fermi motion, nucleon correlations, non-QEL interactions and FSI. If FSI effects and nucleon correlations are neglected,  $\delta\mathbf{p}$  coincides with the initial nucleon momentum  $\mathbf{p}_{N_i}$ . Moreover,  $\delta\alpha_T$  is uniform due to the isotropic nature of the Fermi motion. FSI effects smear the  $\delta\mathbf{p}_T$  distribution and modify the shape of the  $\delta\alpha_T$  distribution. In GENIE, the  $hA$  FSI model enhances the cross section at  $\delta p_T > 0.2$  GeV/c and  $\delta\alpha_T \sim 180^\circ$ ; see Fig. 30. This region is referred to as high-transverse kinematic imbalance region.

Ref. [37] demonstrated that the  $\delta p_T$  and  $\delta\alpha_T$  dependence on the neutrino energy is smaller than possible uncertainties due to FSI modeling. The  $\delta\phi_T$  variable has a stronger dependence on the neutrino energy as it scales with  $\delta p_T/p_T^\mu$ : at higher neutrino

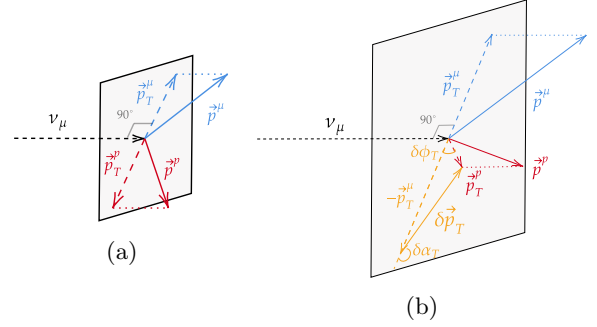


FIG. 29: Graphical definition of the STKI variables in a  $\nu_\mu$  CCQEL neutrino interaction on a nuclear target. The incoming neutrino, represented as a dashed arrow, interacts with a free nucleon at rest (a) or with a bound nucleon subject to Fermi motion (b). The outgoing muon (proton) is represented in blue (red). The transverse plane is represented in grey. The incoming neutrino is perpendicular to the transverse plane. Nuclear effects distort the free-nucleon picture (a) creating an imbalance between the muon and nucleon transverse momentum (b). The STKI variables that define this imbalance are highlighted in orange.

energies, the distribution at small angles becomes narrower. The dependency of the STKI variables in GENIE with the neutrino energy is shown in Fig. 31. Changes in the neutrino energy affect mostly the tail of the  $\delta p_T$  distribution and the  $\delta\alpha_T$  distribution at backward angles.

## Appendix B: Comparisons G18\_10\_02.11b against neutrino-nucleus CC0 $\pi$ data

This section offers with comparisons of GENIE against all CC0 $\pi$  and CCNp0 $\pi$  data available from MiniBooNE, T2K, MINERvA and MicroBooNE. The corresponding GENIE predictions are obtained by replicating the analysis within GENIE: neutrino interaction events are simulated for each experiment given the neutrino flux, target material, and analysis cuts. The normalized neutrino flux spectra is reported in Fig. 1. With this information, the GENIE prediction for the corresponding differential flux-integrated cross section is evaluated.

The format of all the comparisons with data reported in this appendix is common: the data and differential cross-section prediction are represented in black. In addition, the contribution from different interaction models is shown for CCRES, CC2p2h and CCDIS/SIS. The contribution to the G18\_10a\_02.11b predictions from CCDIS/SIS events

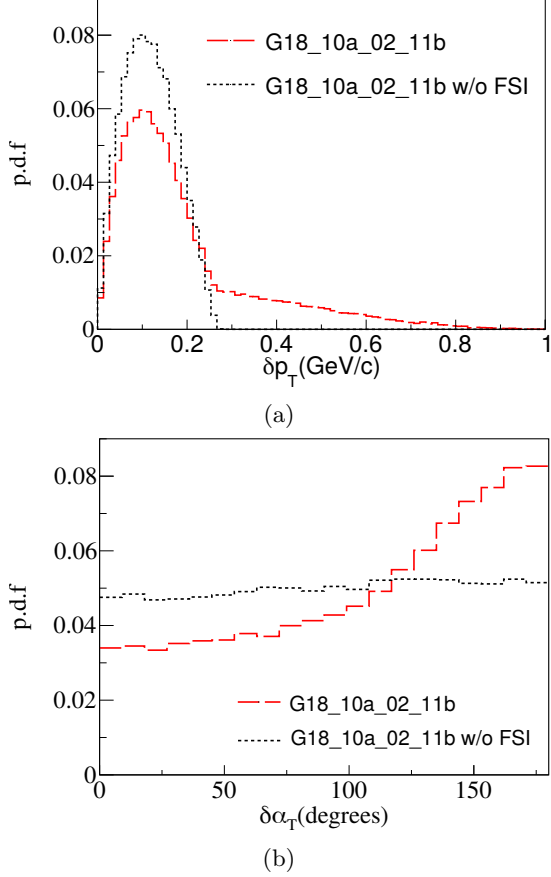


FIG. 30: Probability density function of  $\delta p_T$  and  $\delta \alpha_T$  for the G18\_10a\_02\_11b tune with (a) and without (b) FSI. Both predictions are obtained simulating  $\nu_\mu$  CCQEL interactions only on  $^{12}\text{C}$  at 1 GeV with the G18\_10a\_02\_11b tune.

is really small at the neutrino energies considered in this work. For this reason, the contribution is grouped into a single category (DIS). The 2p2h contribution is divided further into four categories that depend on the event invariant mass,  $W$ . The  $W$  regions are:

- $W < M_N = 938 \text{ MeV}/c^2$
- $M_N < W < W_{\text{Dip}} = 1120 \text{ MeV}/c^2$
- $W_{\text{Dip}} < W < M_\Delta = 1232 \text{ MeV}/c^2$
- $W > M_\Delta$

The data error bars include statistical and systematic uncertainties. The errors on the  $x$ -axis represent the bin width used in the original analysis.

### 1. MiniBooNE CC0 $\pi$ cross-section measurement

The MiniBooNE experiment studies neutrinos produced with the BNB [7]. MiniBooNE provided

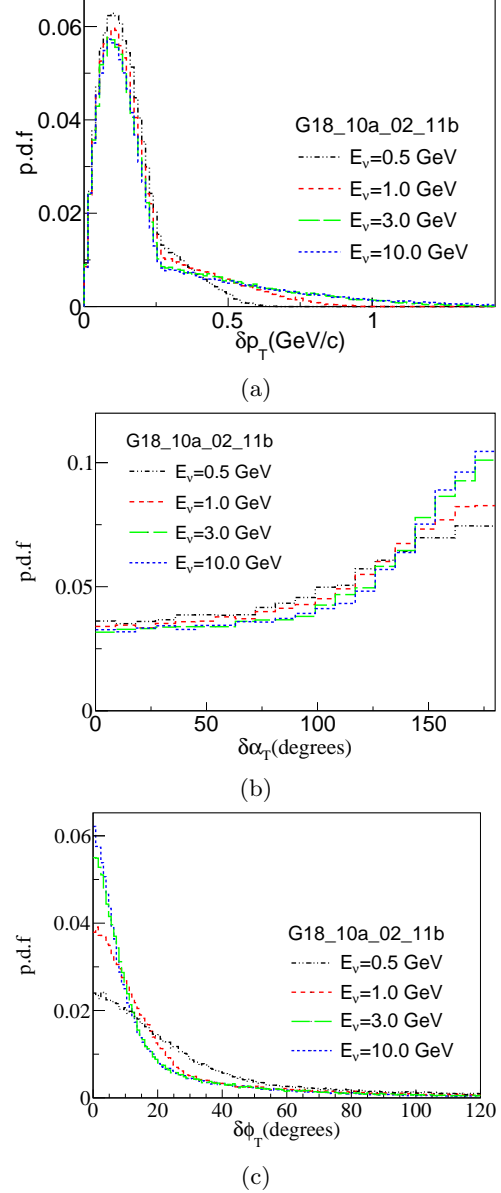


FIG. 31: Probability density function of STKI variables. The predictions are obtained simulating  $\nu_\mu$  CCQEL interactions only on  $^{12}\text{C}$  with the G18\_10a\_02\_11b tune at different neutrino energies.

with the first-high statistics  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC0 $\pi$  flux-integrated double differential cross-section measurement on carbon, at  $\langle E_\nu \rangle \sim 800 \text{ MeV}$  and  $\langle E_{\bar{\nu}} \rangle \sim 500 \text{ MeV}$  respectively [25, 26]. Flux-unfolded total cross section,  $\sigma(E_\nu^{\text{QEL}})$ , and flux-integrated single differential cross section as a function of the squared four-momentum transferred,  $d\sigma/dQ_{\text{QEL}}^2$ , were also reported.

Both MiniBooNE analyses study CC0 $\pi$  events with a muon in the final state and no pions. The sig-

nal topology of a muon in the detector is described in two sub-events: the first one associated with the primary Cherenkov light from the muon, and the second one, produced by the Cherenkov light from the Michel electron, which is produced in the muon decay. This requirement provides a sample of mostly CC events, as neutral-current events only have one sub-event.

Positively charged pions produced in the detector leave a distinct signature in the detector, as the  $\pi^+$  decays immediately into a muon and a muon neutrino. The Cherenkov light from the  $\pi^+$  contributes to the total light of the primary muon. This process can be distinguished from a CCQEL interaction as the muon produced from the pion decay will also decay into a Michel electron (three sub-events). Negatively charged pions are absorbed by the nuclear environment and contribute to the  $CC0\pi$  topology. In the GENIE predictions, pion production events are removed by requiring no pions in the final state.

Recoil protons also emit scintillation light. However, such scintillation light signal produced is either indistinguishable from the muon signal or its momentum below the Cherenkov threshold. For this reason, no requirements based on the recoil proton are considered in the MiniBooNE analyses.

The analysis considers further model-dependent cuts to correct for backgrounds and extract the CCQEL cross-section from the  $CC0\pi$  sample. In the original publication, these are referred to as *irreducible backgrounds*. An example of irreducible background is  $CC1\pi$  events that were not removed by the cut on the pion subevent topology or pion production events in which the pion is absorbed. This is corrected using a MC simulation tuned to  $\nu_\mu$   $CC1\pi$  MiniBooNE data. Information on  $\nu_\mu$   $CC1\pi^+$  sample is used to characterize this background and correct for single-pion events which were not removed by the  $CC0\pi$  selection criteria in the neutrino and antineutrino analyses. This procedure is one of the main limitations of this dataset as it incorporates strong biases in the reported measurement. The contribution to the cross-section measurement from irreducible backgrounds is also reported, allowing the comparison against  $CC0\pi$  data.

The quality of the MiniBooNE  $CC0\pi$  data release is poor in comparison with the rest. The MiniBooNE collaboration provided measurements in bins of  $T_\mu$  and  $\cos\theta_\mu$ , but did not provide the bin-to-bin covariances for either of the two measurements. Instead, they quoted a normalization systematic uncertainty of  $\sim 10.7\%$ . As suggested by Ref. [25], this error is added as a systematic in our database, effectively including a correlation between the bins.

In Figs. 2 and 32, the flux-integrated double differential  $\nu_\mu$  and  $\bar{\nu}_\mu$   $CC0\pi$  cross section data as a

function of  $p_\mu$  and  $T_\mu$  are compared against GENIE. The main observation is that the GENIE tune underpredicts the data. In particular, the G18\_10a\_02\_11b disagreement with the data are more significant at backward angles, where the cross-section is determined by CCQEL events only. The disagreement is also observed at forward angles, where there is a significant contribution from non-QEL events.

## 2. T2K ND280 $CC0\pi$ cross-section measurements

The Tokai-to-Kamioka (T2K) experiment is an accelerator-based long-baseline experiment that studies neutrino oscillations. Neutrinos are generated at the Japan Proton Accelerator Research Complex (J-PARC) facility [6], 280 m away from the T2K near detectors [2]: INGRID and ND280. The T2K ND280 detector is used to measure neutrino interactions on carbon at  $\langle E_\nu \rangle \sim 600$  MeV. Details on the detector setup can be found in Ref. [27]. The measurements described here use the detector central tracker region, composed of three time projection chambers (TPC) and two fine-grained detectors (FGD1 and FDG2). The FGDs are the target mass and are also used to track charged particles. Carbon measurements use the FGD1 as the target mass. The central region is surrounded by an electromagnetic calorimeter (ECal), which is contained within a magnet. This setup allows measuring the particle charge and momentum. This information, together with energy deposition, is used to identify charged particles.

The first double-differential  $CC0\pi$  measurement provided by T2K ND280 was released back in 2015 [38]. This measurement is surpassed by Ref. [27], which considers improved constraints on systematic uncertainties. Ref. [27] provides additional measurements including double- and triple-differential measurements for different proton multiplicities as well as two  $CCNp0\pi$  single-differential cross-section measurements as a function of STKI and *proton inferred kinematics* quantities.

All measurements from Ref. [38] require one muon and no pions in the final state, regardless of the number of nucleons in the event. Any event must contain at least one track in the TPC, which must be either a muon or a proton. If it is a proton, they look for a muon-like track in the FGD1 or ECal. Other events with tracks that are not consistent with the muon-like or proton-like signature are rejected. Events with low-momentum charged or neutral pions are removed by requiring no Michel electrons or photons. At the MC level, this is implemented by removing events with pions or photons in the final

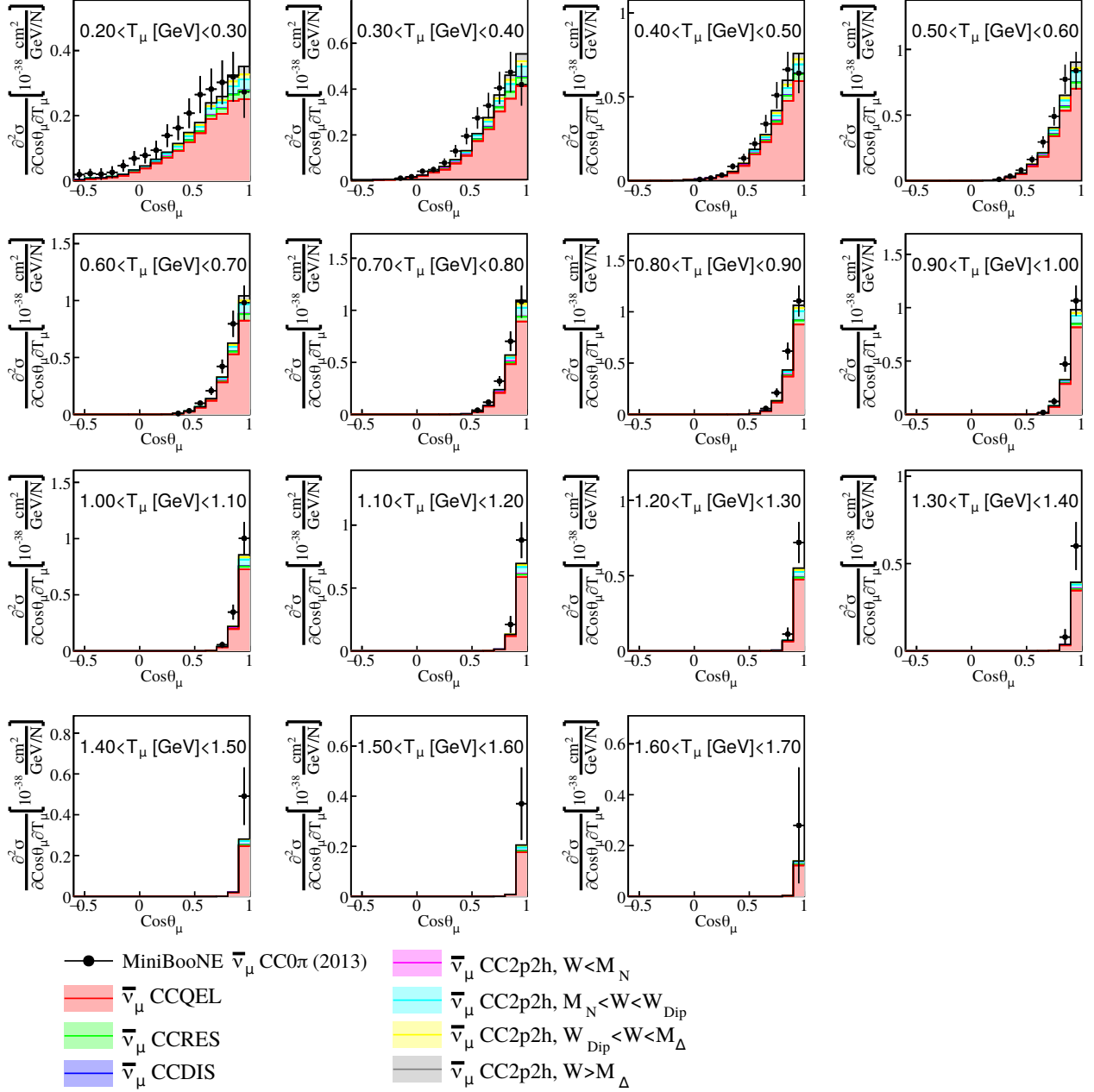


FIG. 32: MiniBooNE  $\bar{\nu}_\mu$  CC0 $\pi$  double differential flux-averaged cross section as a function of the muon angle,  $\theta_\mu$ , and kinetic energy,  $T_\mu$  [26]. The corresponding slices on  $T_\mu$  are compared against the G18\_10a\_02\_11b tune. The GENIE prediction is divided into different categories: CCQEL, CCRES, CC2p2h and CCDIS.

state, respectively.

The selected sample is divided further depending on the number of protons above the detection threshold of 500 MeV/c: no protons (CC0p0 $\pi$ ), one proton (CC1p0 $\pi$ ) or more than one visible proton (CC2p0 $\pi$ ) in the final state. The CC0p0 $\pi$  and CC1p0 $\pi$  are double- and triple-differential cross-section measurements as a function of the muon and muon and

proton kinematics respectively. The total CC2p0 $\pi$  cross-section is also reported. The STKI and *proton inferred kinematics* are obtained with the CCNp0 $\pi$  sample: they require the presence of at least one visible proton ( $p_p > 500$  MeV/c).

Efficiency corrections for CCNp0 $\pi$  events can be very model dependent. To avoid this, different kinematical restrictions are considered for each analysis,

TABLE IX: Phase-space restrictions for the T2K ND280 analyses from Ref. [27]. The proton cuts are only applied to the highest energy proton.

T2K ND280 Analysis	$p_p$	$\cos \theta_p$	$p_\mu$	$\cos \theta_\mu$
CC0p0 $\pi$	< 500 MeV/c (or no proton)			
CC1p0 $\pi$	> 500 MeV/c			
CCNp0 $\pi$ , STKI	$450 < p_p < 1000$ MeV/c	> 0.4	> 250 MeV/c	> -0.6
CCNp0 $\pi$ , proton inferred kinematics	> 450 MeV/c	> 0.4		

selecting regions in which the efficiency is flat or well understood. These are specified in Tab. IX. Events with more than one proton are reconstructed using the information from the highest energy one, which has to satisfy the kinematical limits of Tab. IX. The samples are not corrected for events with protons below the detection threshold or any of the kinematical cuts considered in the analysis. The same cuts are applied at the generator level when evaluating the GENIE predictions.

The GENIE comparison against the  $\nu_\mu$  CC0p0 $\pi$  double-differential cross section are presented in Fig. 33. The main contribution to the CC0p0 $\pi$  topology comes from CCQEL events. The second contribution is from CC2p2h events with  $M_N < W < W_{\text{Dip}}$ . The contribution from 2p2h events with  $W < M_N$  or  $W > W_{\text{Dip}}$  is negligible for the CC0p0 $\pi$  measurement. GENIE is under-predicting the data at backward angles.

This disagreement in the overall normalization is also observed in Fig. 5, which compares GENIE against the cross-section as a function of the proton multiplicity. This observation conflicts with  $\nu_\mu$  CC1p0 $\pi$  data, which is not under-predicted. There are some outstanding differences between the GENIE predictions for CC0p0 $\pi$  and CC1p0 $\pi$  data. Whilst the total contribution from 2p2h events is similar, the main 2p2h contribution comes from 2p2h events with  $W > W_{\text{Dip}}$ . In addition, the fraction from RES events is higher with respect to the CC0p0 $\pi$  one.

Fig. 34 provides comparisons against  $\nu_\mu$  CCNp0 $\pi$  data as a function of the STKI variables, concluding that non-QEL interactions are essential to describe this data within regions of high transverse kinematic imbalance.

### 3. MINERvA CC0 $\pi$ cross-section measurements

MINERvA studies neutrino interactions on nuclear targets for neutrino and antineutrino inter-

actions at  $\sim 1 - 10$  GeV at Fermilab [61, 62]. MINERvA's detector is composed of a segmented scintillator detector surrounded by electromagnetic and hadronic calorimeters. The detector is situated 2.1 m upstream of the MINOS near detector [63], which is a magnetized iron spectrometer. MINOS is used to reconstruct the muon momentum and charge.

Neutrinos are generated at the NuMI beamline [8]. This beam has two configurations: *low energy* flux ( $\langle E_\nu \rangle \sim 3.5$  GeV) and *medium energy* flux ( $\langle E_\nu \rangle \sim 6$  GeV). The NuMI beam can operate in neutrino mode (FHC) and antineutrino mode (RHC). The FHC and RHC *low energy* flux predictions are shown in Fig. 1.

MINERvA extracted several CC0 $\pi$  and CCNp0 $\pi$  measurements using the NuMI *low-energy* flux [28–30, 36]. A CC0 $\pi$  measurement using the NuMI *medium energy* flux is also available [33]. This review focuses on the CC0 $\pi$  and CCNp0 $\pi$  measurements obtained with the *low-energy* flux.

The exact target mixture is composed of carbon (88.51%), hydrogen (8.18%), oxygen (2.5%), titanium (0.47%), chlorine (0.2%), aluminium (0.07%), and silicon (0.07%). In the calculation of the GENIE predictions, only the three most abundant targets are considered. The relative mass abundances are renormalized to take this approximation into account. This simplifies the computing power and has a negligible effect on our predictions.

#### a. MINERvA $\nu_\mu$ and $\bar{\nu}_\mu$ CC0 $\pi$ cross-section measurement

MINERvA reported the CC0 $\pi$  differential flux-integrated cross-section as a function of muon momentum in the transverse ( $T$ ) and longitudinal ( $\parallel$ ) direction relative to the neutrino beam [28, 36]. The differential cross-section as a function of  $E_\nu^{\text{QEL}}$  and  $Q_{\text{QEL}}^2$  are reported as well [64]. The neutrino energy and the momentum transferred are reconstructed under the QEL hypothesis, described in Sec. A 2.



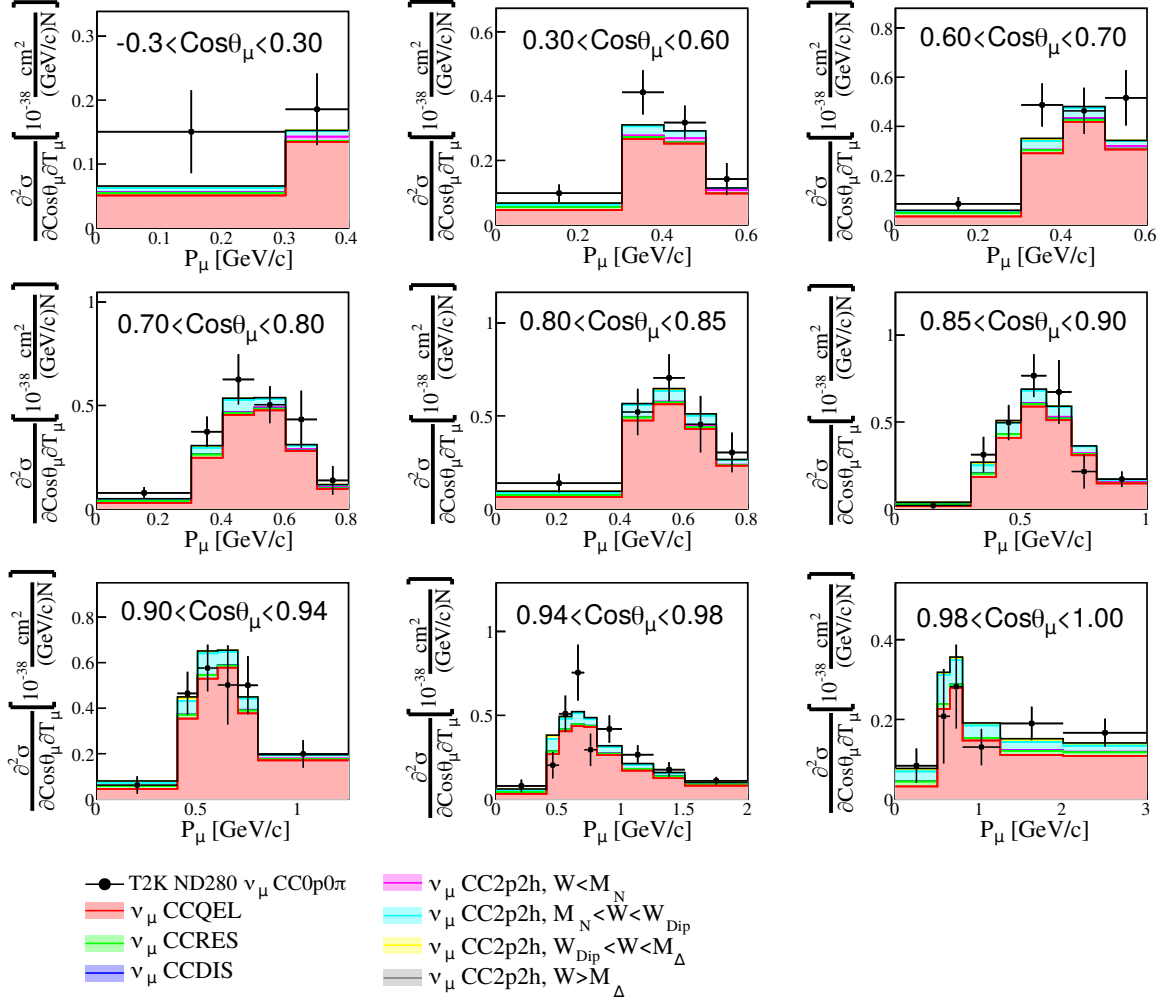


FIG. 33: T2K ND280 flux-averaged  $\nu_\mu$  CC0p0 $\pi$  differential cross section as a function of the proton multiplicity [38]. The data are compared against the G18.10a.02.11b tune. The GENIE prediction is divided into different categories: CCQEL, CCRES, CC2p2h and CCDIS. For readability, the CC0p0 $\pi$  high energy bins are not included in these plots.

The binding energy used to reconstruct  $E_\nu^{\text{QEL}}$  according to Eq. A1 in their neutrino and antineutrino analysis is  $E_b = 34$  MeV and  $E_b = 30$  MeV respectively.

The  $\nu_\mu$  CC0 $\pi$  topology is defined as an event with one muon,  $\mu^-$ , any number of protons and neutrons, any photons below nuclear de-excitation energies,  $E_\gamma \leq 10$  MeV, no mesons and no heavy or excited baryons in the final state. The MINERvA detector is not able to measure the muon charge as it does not have a magnetic field. For this reason, muons are identified by looking for tracks that have a match with the MINOS detector, which is used to determine the muon momentum and charge. Because of geometric acceptance, both analyses require  $\theta_\mu < 20^\circ$ . Events containing low-energy photons are accepted as they can arise from nuclear de-

excitation. Pions are removed by applying a cut on the recoil energy,  $E_{\text{recoil}} \leq 500$  MeV, defined as the activity that is not coming from a muon or any tracked protons.  $E_{\text{recoil}}$  is corrected for the calorimetric detector response [36]. The recoil energy does not include energy deposited at less than 150 mm from the neutrino vertex as it could be due to proton absorption nearby the vertex. Moreover, events with Michel electrons are removed, as they assume they come from a  $\pi$  decay chain ( $\pi \rightarrow \mu \rightarrow e$ ).

The  $\bar{\nu}_\mu$  CC0 $\pi$  topology [36] is similar to the  $\nu_\mu$  one, with some differences. Due to the nature of this interaction, the muon must be positively charged. Moreover, the analysis requires to have no visible protons in the final state, i.e. protons with kinetic energy above 120 MeV. Finally, mesons are removed using the information on the recoil energy deposited

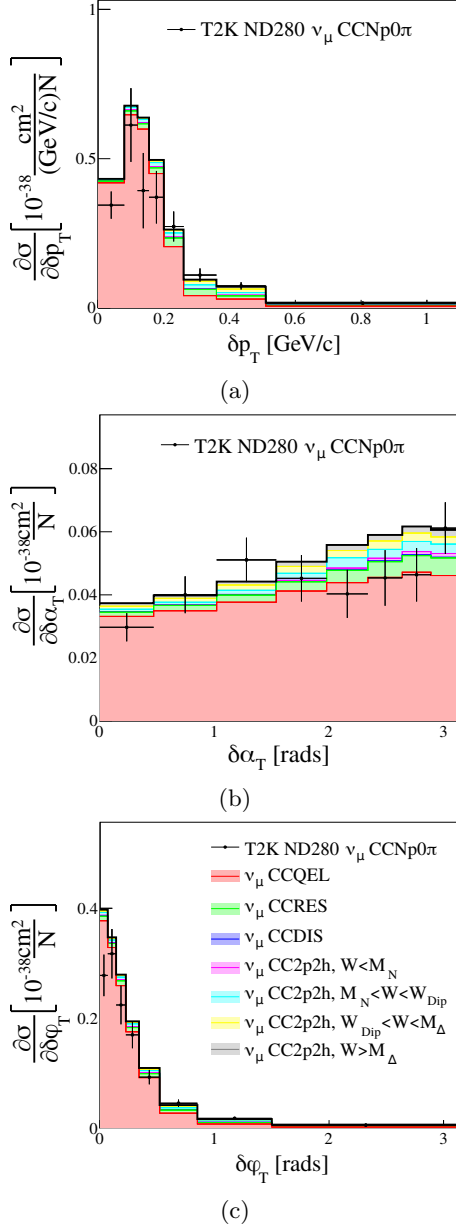


FIG. 34: T2K ND280 flux-averaged  $\nu_\mu$  CCNp0 $\pi$  differential cross section as a function of STKI variables [38]. The data are compared against the G18\_10a\_02\_11b tune. The GENIE prediction is divided into different interaction categories: CCQEL, CCRES, CC2p2h and CCDIS.

outside the vertex region only.

The GENIE prediction is evaluated with MC events that satisfy the criteria specified above with few exceptions: the removal of events with mesons in the final state is based on true information only. Baryons, are short living and decayed into mesons using the GENIE particle decayer. The require-

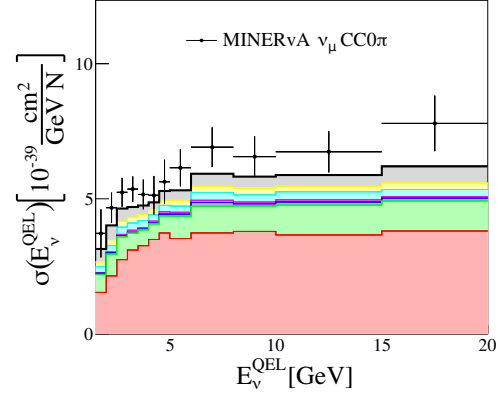


FIG. 35: MINERvA  $\nu_\mu$  CC0 $\pi$  flux-averaged cross-section as a function of reconstructed neutrino energy,  $E_\nu^{\text{QEL}}$  [28]. The data are compared against the G18\_10a\_02\_11b tune.

ments on the removal energy are not implemented in our MC analysis either as the data was already corrected for this effect.

GENIE comparisons against the double-differential  $\nu_\mu$  CC0 $\pi$  measurement is shown in Figs. 3 and 36 for  $\bar{\nu}_\mu$  CC0p0 $\pi$  data. For both  $\nu_\mu$  and  $\bar{\nu}_\mu$  data, the G18\_10a\_02\_11b underestimates the data. This is true especially in the phase-space regions in which 2p2h events dominate. In high  $p_T$  regions, where the contribution of 2p2h events is negligible, the agreement improves. This can be seen for the  $0.85 < p_T < 2.5$  GeV/c slices in Fig. 3. Consequently, the reconstructed neutrino energy is also under-predicted, as observed in Fig. 35.

#### b. MINERvA $\nu_\mu$ CCNp0 $\pi$ production cross-section measurement

The MINERvA Collaboration released two CCNp0 $\pi$  analyses: single-differential cross-section measurements as a function of  $\delta p_T$ ,  $\delta p$ ,  $\delta\alpha_T$  and  $\delta\phi_T$  [29], and a single-differential measurement as a function of  $\delta p_{T,y}$  or  $\delta p_{T,x}$ , respectively [30].

In both analyses, the topology is defined as events with a muon, no mesons and at least one proton in the final state that satisfy the following conditions:

$$1.5 \text{ GeV}/c < p_\mu < 10 \text{ GeV}/c \text{ and } \theta_\mu < 20^\circ,$$

$$0.45 \text{ GeV}/c < p_p < 1.2 \text{ GeV}/c \text{ and } \theta_p < 70^\circ,$$

where  $p_\mu$  ( $p_p$ ) and  $\theta_\mu$  ( $\theta_p$ ) are the muon (lead proton) momentum and opening angle with respect to the neutrino direction. The lead proton is defined as the proton with the highest energy that satisfies the phase space cuts mentioned above.

In this case, the G18\_10a\_02\_11b tune is not under-predicting the data, see Fig. 4 and Fig. 37.

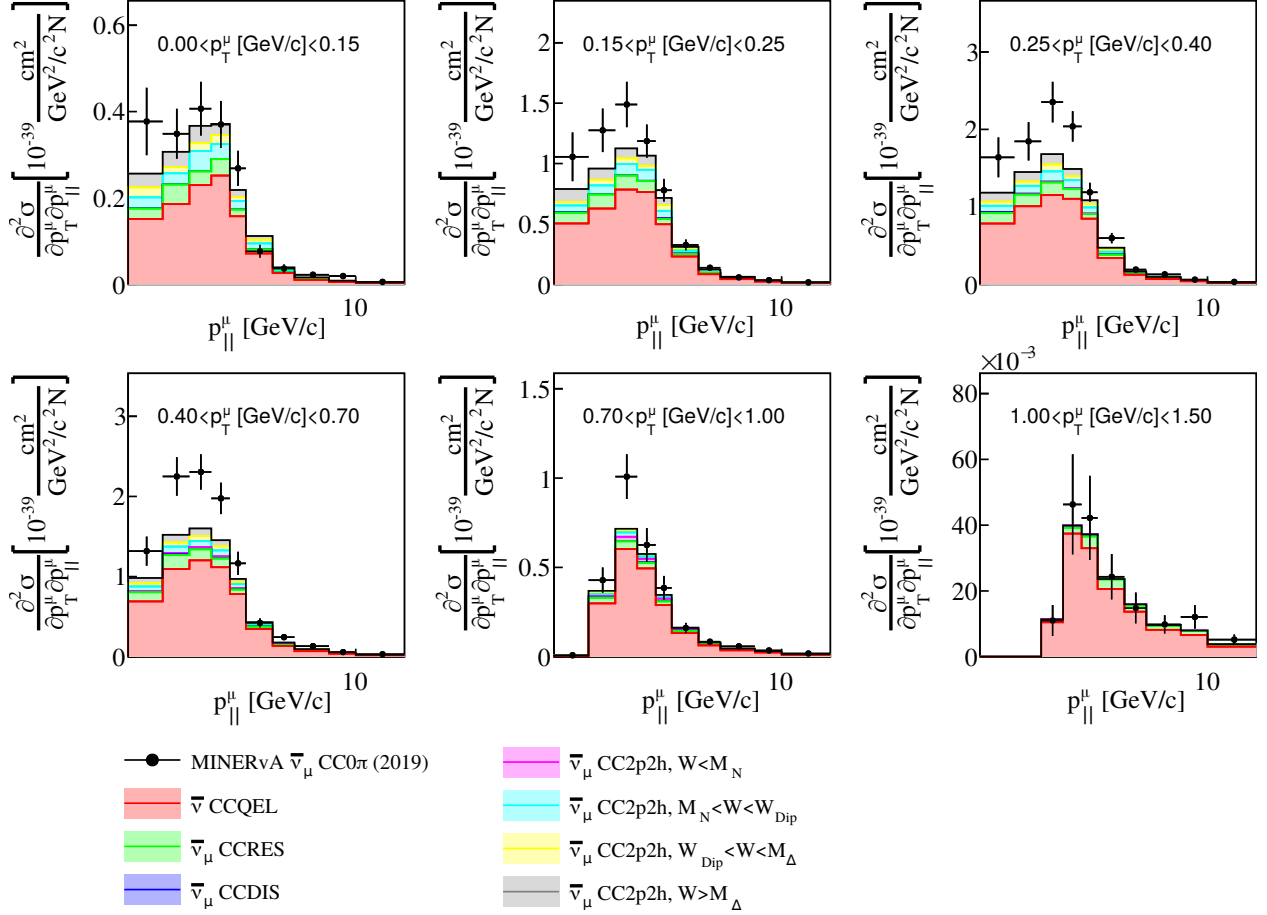


FIG. 36: MINERvA  $\bar{\nu}_\mu$  CC0 $\pi$  double differential flux-averaged cross-section as a function of the muon longitudinal momentum,  $p_{||}$ , and transverse momentum,  $p_T$  [28]. The corresponding slices on  $p_T$  are compared against the G18\_10a\_02\_11b tune. The GENIE prediction is divided into different interaction categories.

This fact, already observed in T2K data, reflects a possible tension between CC0 $\pi$  and CCNp0 $\pi$  measurements. The breakdown into different interaction modes highlights the 2p2h model dependence with  $W$  at different proton momenta: 2p2h events with low (high)  $W$  dominate at low (high) proton momentum. The contribution from RES events is most significant for low proton momenta, small proton angles and  $\delta\alpha_T \sim 180^\circ$ . In fact, non-QEL events dominate in regions of high transverse kinematic imbalance, such as  $\delta p_T > 0.2$  GeV/c.

#### 4. MicroBooNE CCNp0 $\pi$ cross-section measurement

The MicroBooNE experiment is a Liquid Argon Time Projection Chamber (LArTPC) detector situated 500 m away from the BNB beam at Fermilab [3, 7]. LArTPC detectors use complex software

algorithms to reconstruct the neutrino event topology with excellent spatial resolution in the detector [65–67]. For instance, MicroBooNE can reconstruct proton tracks of 2 cm with a  $\sim 26\%$  efficiency [35]. Different Particle IDentification (PID) algorithms, based on the characteristic signal of each particle in the detector, allow the identification of proton and  $\mu/\pi$  candidates, but these methods fail to distinguish between muons and pions.

MicroBooNE provides the first high-statistics cross-section measurements on argon:  $\nu_\mu$  CC inclusive [68],  $\nu_\mu$  CC1p0 $\pi$  [69],  $\nu_\mu$  CCNp0 $\pi$  [35], and  $\nu_\mu$  CC  $\pi^0$  production [70]. The detector is situated 500 m away from the BNB beam at Fermilab [7]. In this section, we focus on the description of the CCNp0 $\pi$  measurement [35], given that the CC1p0 $\pi$  measurement [69] is a subsample of the CCNp0 $\pi$  one.

The CCNp0 $\pi$  analysis presents a total of five single differential flux-integrated cross-section measure-

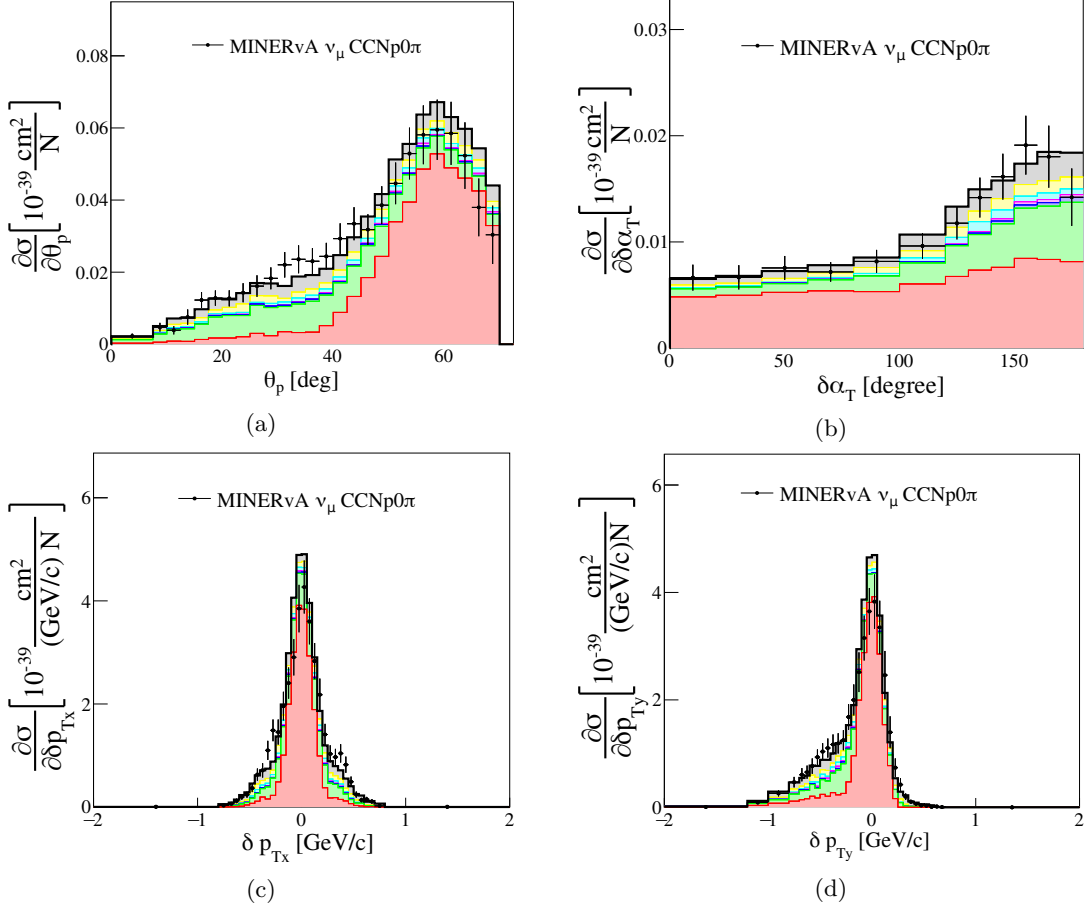


FIG. 37: MINERvA  $\nu_\mu$  CCNp0 $\pi$  differential flux-averaged cross-section as a function of STKI variables [29, 30]. The data are compared against the G18\_10a\_02\_11b tune. The GENIE prediction is divided into interaction modes.

ments. The single differential cross sections are given in terms of the muon momentum ( $p_\mu$ ), muon angle ( $\theta_\mu$ ), leading proton momentum ( $p_p$ ), leading proton angle ( $\theta_p$ ), and the angle between the muon and the leading proton ( $\theta_{\mu p}$ ).

The CCNp0 $\pi$  topology is defined as an event with one muon, at least one visible proton, any number of neutrons and no pions in the final state. In the analysis, the muon candidate is the longest track which is not identified as a proton. Other tracks in the event must be compatible with the proton PID hypothesis. In order to guarantee at least a 5% efficiency in the momentum reconstruction, they require the muon (proton) to have a momentum of at least 100 MeV/c (300 MeV/c). In addition, the leading proton candidate is must have a reconstructed momentum of less than 1.2 GeV/c. This cut avoids regions of the phase-space in which the proton candidate length is greater than the muon one. These analysis criteria removes events with pions below 30 MeV/c, which are not reconstructed. No corrections are applied to

remove events with protons or pions below the detection threshold. The same requirements are applied to the corresponding MC predictions.

The differential cross-section measurements were not unfolded to true muon momentum and muon angle. Instead, the results are presented in terms of the reconstructed quantities. The smearing matrices that convert from the reconstructed to the truth quantities are provided in the data release and are used for the evaluation of the GENIE predictions in the reconstructed space [35]. This method is known as *forward folding*.

Figure 38 presents the comparison between the MicroBooNE data and the GENIE predictions. The nominal agreement for the G18\_10a\_02\_11b tune is reasonably good, except for the bin at highest  $\cos\theta_\mu^{\text{reco}}$ , which is largely over-predicted. The contribution of non-QEL interactions increases at forward muon and proton angles, see Figs.38b and 38d. The G18\_10a\_02\_11b dependency on 2p2h events at different  $W$  with the proton momenta is

re-encountered.

### Appendix C: Additional Nuclear Uncertainties

Here, we explore modeling aspects that were not included in the tuning exercise.

#### 1. Nuclear model implementation

Uncertainties in the nuclear model affect the dynamics of the outgoing muon and nucleon after a QEL or a 2p2h interaction.

In the Valencia model implementation in GENIE, the differential cross section is evaluated at an effective energy transfer  $\tilde{q}_0$ , which takes into account the nucleon removal energy. The implementation in the QEL and 2p2h processes is slightly different. The effective energy transfer  $\tilde{q}_0$  used in the Valencia QEL model implementation is:

$$\tilde{q}_0 = q_0 + E_{N_i} - E_p = E_{N_f} - E_p \quad (\text{C1})$$

$E_{N_i}$  is the energy of the off-shell initial nucleon, which is bound with a binding energy  $E_b$ .  $E_p$  is the energy of the initial nucleon on-shell with a momentum  $\mathbf{p}$ ,  $E_p = \sqrt{M_N^2 + \mathbf{p}^2}$ .  $E_{N_f}$  is the energy of the nucleon produced after the QEL interaction, which is on-shell. In other words, the effective energy transfer is reduced relative to the ordinary one by the amount of energy needed to put the initial nucleon on the mass shell. The binding energy and initial nucleon momentum are determined by the corresponding nuclear model. In this work, for QEL interactions we refer to  $\tilde{q}_0$  as  $\tilde{q}_0^{\text{QEL}}$ . Notice that  $\tilde{q}_0^{\text{QEL}}$  depends on the event kinematics.

In the Valencia 2p2h model implementation, the effective energy transfer is calculated as:

$$\tilde{q}_0 = q_0 - q_{\text{shift}}^{2\text{p2h}}, \text{ where } q_{\text{shift}}^{2\text{p2h}} \equiv M(A_{Z+1}) - M(A_Z).$$

In this case,  $q_{\text{shift}}^{2\text{p2h}}$  is independent of the event kinematics. For a carbon target,  $q_{\text{shift}}^{2\text{p2h}}(^{12}\text{C}) = 16.8$  MeV, whilst  $q_{\text{shift}}^{2\text{p2h}}(^{40}\text{Ar}) = 0.99$  MeV for argon.

Shifts on  $\tilde{q}_0$  are effective modifications of the binding energy in the nuclear model. It is possible to apply relative shift to  $\tilde{q}_0$  for both QEL and 2p2h calculations by modifying  $q_0^{\text{QEL}}$  and  $q_{\text{shift}}^{2\text{p2h}}$ . This modification translates as:

$$\begin{aligned} \tilde{q}_0^{\text{QEL}} &\rightarrow \tilde{q}_0^{\text{QEL}}(1 + f^{\text{QEL}}) \\ q_{\text{shift}}^{2\text{p2h}} &\rightarrow q_{\text{shift}}^{2\text{p2h}}(1 + f^{2\text{p2h}}) \end{aligned}$$

$f^{\text{QEL}}$  and  $f^{2\text{p2h}}$  are two dimensionless parameters. In the GENIE v3 version, both parameters default

to 0. Both  $f^{\text{QEL}}$  and  $f^{2\text{p2h}}$  parameters are included in the initial iteration of this analysis.

Ref. [71] suggests that shifts on  $\tilde{q}_0^{\text{QEL}}$  ( $q_{\text{shift}}^{2\text{p2h}}$ ) of 0–20 MeV (0–40 MeV) for QEL (2p2h) are in reasonable agreement with electro-scattering data. The effect of such variations on the 2p2h cross-section prediction is shown in Fig. 39. The biggest variation is observed on  $d\sigma/dQ^2$  for both QEL and 2p2h. For the 2p2h cross section, this systematic shifts peaks position in  $W$ .

#### 2. Final state interaction implementation

Final-state interactions (FSI) are crucial for modeling nuclear cross sections as they affect the event topology and kinematics of an event. There are different models available in GENIE to simulate FSI [14, 46]. In particular, G18\_10a\_02\_11b models FSI with the INTRANUKE  $hA$  model [22].

INTRANUKE  $hA$  is an empirical model that considers a single interaction which is based on hadron-nucleus data [46]. In particular, pion-nucleus data are used to determine the inelastic (Inel), absorption (Abs), charge-exchange (CEX) and pion production ( $\pi$ Prod) fractions ( $f_i$ ). The fractions depend on the pion kinetic energy and the nuclear atomic number. These fractions satisfy that  $\sum_i f_i^{\pi^\pm} = 1$  (unitarity condition), where  $i$  is an index that runs over the available processes aforementioned.

Two parameters are introduced to be able to modify the  $f_{\text{Abs}}^{\pi^\pm}$  and  $f_{\text{Abs}}^{\pi^0}$  while preserving unitarity:

$$f'_{\text{Abs}}{}^{\pi^\pm} = \frac{S_{\text{Abs}}^{\pi^\pm} \cdot f_{\text{Abs}}^{\pi^\pm}}{f_{\text{Inel}}^{\pi^\pm} + S_{\text{Abs}}^{\pi^\pm} \cdot f_{\text{Abs}}^{\pi^\pm} + f_{\text{CEX}}^{\pi^\pm} + f_{\pi\text{Prod}}^{\pi^\pm}}$$

The other fractions are also modified as a consequence of this scaling. Notice that variations of  $S_{\text{Abs}}^{\pi^\pm}$  do not scale  $f'_{\text{Abs}}{}^{\pi^\pm}$  linearly.

Similarly, a scaling parameter is introduced to scale the charged pion mean-free path. This is referred to as  $S_{\text{MFP}}^{\pi^\pm}$ . The same approach can be applied to other processes and to nucleon fractions.

Figure 40 shows the dependence of each  $hA$  fraction as a function of the pion kinetic energy ( $T_\pi$ ) for carbon and argon targets. The FSI fractions and their uncertainty are extracted from fits to hadron-nucleus scattering data [46, 72]. The uncertainty associated with  $f_{\text{Abs}}^{\pi^\pm}$  is 15%.

Variations of the FSI parameters considered in this work result in the migration of CC1 $\pi$  events into the CC0 $\pi$  sample. The effect on the prediction depends on the topology definition. For CC0 $\pi$  samples, it mostly affects the overall normalization of the cross-section. The measurement most sensitive to this variation is the  $\nu_\mu$  CCNp0 $\pi$  MINERvA

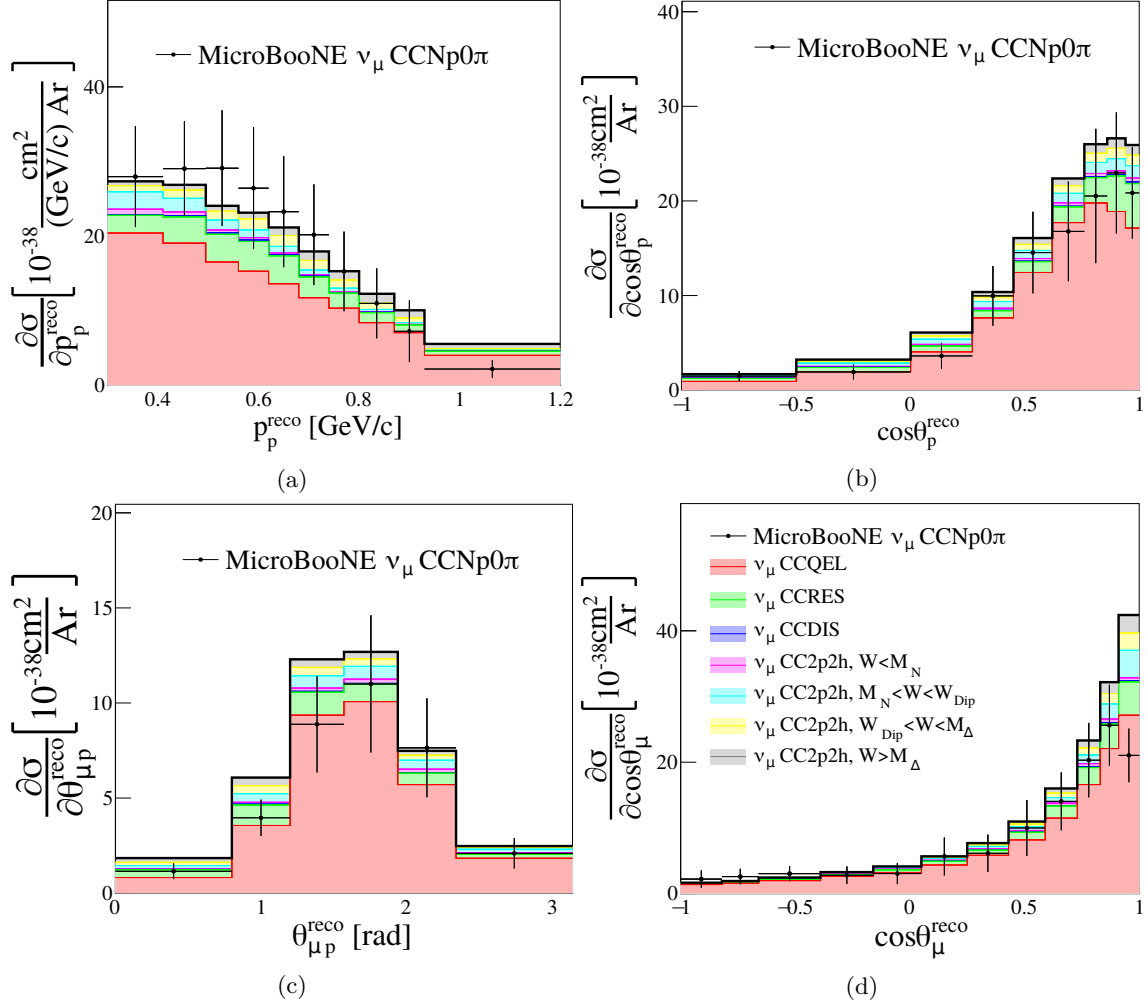


FIG. 38: MicroBooNE  $\nu_\mu$ CCNp0 $\pi$  flux-averaged differential cross section on  $^{40}\text{Ar}$  as a function of muon and proton kinematics. The GENIE prediction is obtained with the G18.10a.02.11b tune. The nominal prediction is divided into interaction modes.

differential cross section as a function of  $\delta\alpha_T$ , see Fig. 41. A decrease in  $S_{\text{Abs}}^{\pi^\pm}$  reduces the cross section at  $\delta\alpha_T \sim 180^\circ$ . In addition, this model variation also affects the slope of the distribution.

In this tune, only parameters related to charged pion absorption are included:  $S_{\text{Abs}}^{\pi^\pm}$  and  $S_{\text{MFP}}^{\pi^\pm}$ . Pion inelastic fractions are not relevant at the energies of interest for this work. Nucleon FSI parameters are relevant for the study of exclusive cross-section measurements with protons in the final state. Ideally, to perform a global tune with CC0 $\pi$  and CCNp0 $\pi$  data, nucleon FSI parameters must be considered in the analysis. Including these parameters in the analysis substantially increases the computing time. In addition, it is desirable to first understand the tensions between CC0 $\pi$  and CCNp0 $\pi$  measurements. Therefore, it is therefore convenient to reduce the com-

plexity of the analysis and focus on CC0 $\pi$  datasets only. Nucleon FSI parameters will be included in future iterations of this work.

### 3. Final choice of parameters for the CC0 $\pi$ tune

A series of preliminary tunes were performed using different priors or parameter sets. The goal of this study is to determine which parameters to include in the final tune.

Nuclear effects in the QEL cross section are tweaked with the RPA parametrization. Free-nucleon cross-section data suggests that the QEL cross section should not be scaled. This condition can be incorporated in our analysis by imposing a more restrictive prior on  $S_{\text{RPA}}$  of  $\sigma_S = 0.01$ . Tunes

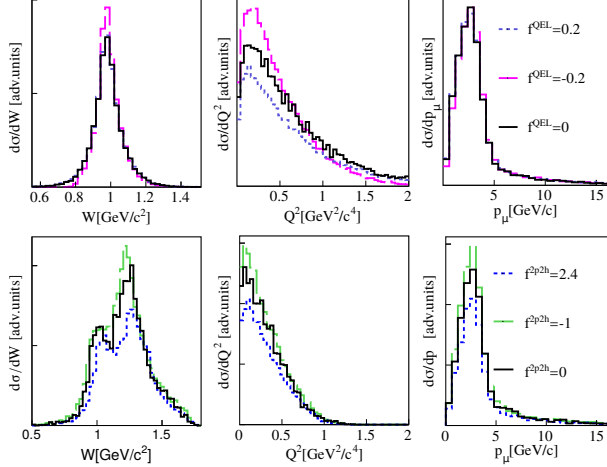


FIG. 39: Flux-integrated differential  $\nu_{\mu}^{12}\text{C}$  CC2p2h cross section dependence with  $W$ ,  $Q^2$  or  $p_{\mu}$ . Events are generated with the G18.10a.02.11b tune and the NuMI  $\nu_{\mu}$  low energy flux [8]. The top (bottom) three plots show the CCQEL (CC2p2h) differential cross section as a function of  $W$ ,  $Q^2$  or  $p_{\mu}$ . The black prediction corresponds to the GENIE v3 case, where no shifts on  $\tilde{q}_0^{\text{QEL}}$  and  $q_{\text{shift}}^{2\text{p}2\text{h}}$  are considered. The variations considered for the  $f^{\text{QEL}}$  and  $f^{2\text{p}2\text{h}}$  parameters correspond to an absolute shift to  $\tilde{q}_0^{\text{QEL}}$  and  $q_{\text{shift}}^{2\text{p}2\text{h}}$  of 20 MeV for QEL interactions and of 40 MeV for 2p2h interactions.

performed using this prior result in worse goodness of fit, suggesting that a less restrictive prior on the sum is desired to improve the agreement with the data. This motivated our choice for a prior on the sum of  $\sigma_S = 0.2$ , as described in Sec. III A.

FSI interactions are important to describe CC0 $\pi$  measurements. Additional parameters must be consistent with previous data [46], making this tricky. The results of test cases with FSI suggest that variations of these parameter that respect pion-nucleus scattering data do not have a big impact on the tune results. Consequently, these parameters are not included in the final analysis.

Various choices were made to get a more representative result. Although full coverage in parameters can be sought, that is not always possible or desirable. For this study, Professor allows a large parameter set which don't have to be ReWeight variables. A study of the  $f^{\text{QEL}}$  and  $f^{2\text{p}2\text{h}}$  parameters in the tune was made. Strong correlations are observed between the  $f^{\text{QEL}}$ ,  $f^{2\text{p}2\text{h}}$  and  $\omega_{\text{RPA}}$  and  $S^{2\text{p}2\text{h}}$  parameters. In some cases, these correlations lead to unphysical values for  $f^{\text{QEL}}$  and  $f^{2\text{p}2\text{h}}$ . For this reason, these parameters are excluded from the analysis.

The final-parameter set used in this work is summarized in Tab. III.

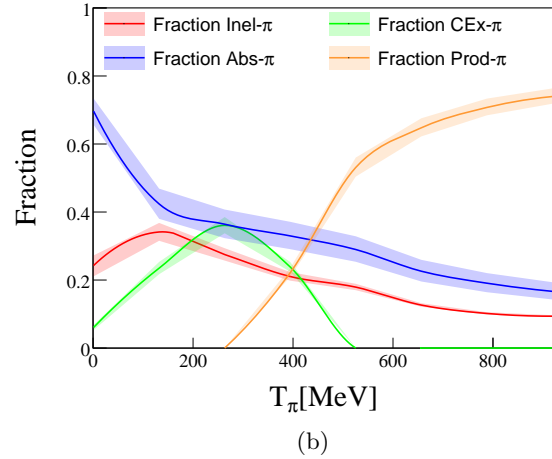
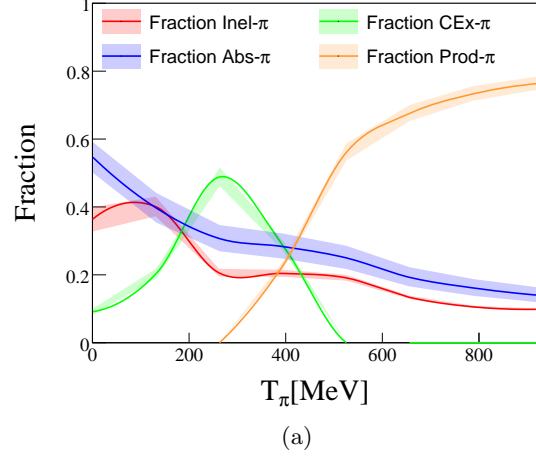


FIG. 40:  $hA$  FSI pion fractions for (a)  $^{12}\text{C}$  and (b)  $^{40}\text{Ar}$  as a function of the pion kinetic energy. The error bands represent the fraction variation when applying a  $S_{\text{Abs}}^{\pi^{\pm}} = 1.2$  on the pion absorption fraction, which corresponds to a variation of  $\sim 15\%$  for the pion absorption fraction on carbon at  $T_{\pi} = 200$  MeV.

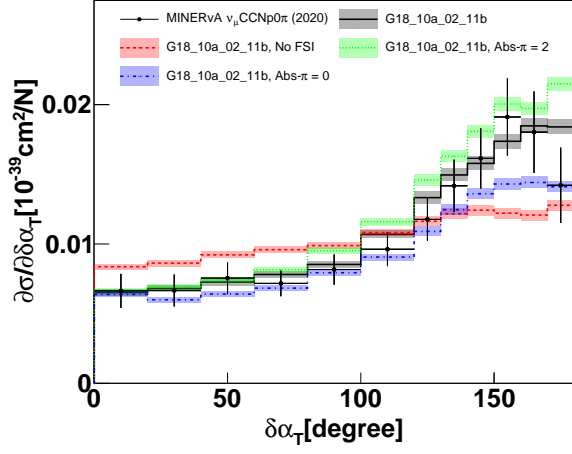


FIG. 41: Impact of  $S_{\text{Abs}}^{\pi^{\pm}}$  on MINERvA CCNp0 $\pi$  flux-integrated differential cross section predictions as a function of  $\delta\alpha_T$ .



- 
- [1] A. Aguilar-Arevalo *et al.*, The miniboone detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **599**, 28–46 (2009).
- [2] K. Abe, N. Abgrall, H. Aihara, *et al.*, The t2k experiment, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **659**, 106 (2011).
- [3] R. Acciarri and others., Design and construction of the microboone detector, Journal of Instrumentation **12** (02), P02017–P02017.
- [4] M. V. Ascencio *et al.* (MINERvA), Measurement of inclusive charged-current  $\nu_\mu$  scattering on hydrocarbon at  $\langle E_\nu \rangle \sim 6$  GeV with low three-momentum transfer (2021), arXiv:2110.13372 [hep-ex].
- [5] J. Tena-Vidal *et al.* (GENIE Collaboration), Neutrino-nucleon cross-section model tuning in genie v3, Phys. Rev. D **104**, 072009 (2021).
- [6] K. Abe *et al.* (T2K Collaboration), T2k neutrino flux prediction, Phys. Rev. D **87**, 012001 (2013).
- [7] A. A. Aguilar-Arevalo, C. E. Anderson, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, and *et al.*, Neutrino flux prediction at miniboone, Physical Review D **79**, 10.1103/physrevd.79.072002 (2009).
- [8] L. Aliaga *et al.* (MINERvA Collaboration), Neutrino flux predictions for the numi beam, Phys. Rev. D **94**, 092005 (2016).
- [9] J. Tena-Vidal *et al.*, Hadronization model tuning in genie v3 (2021), arXiv:2106.05884 [hep-ph].
- [10] P. Abratenko *et al.* (MicroBooNE), New  $CC0\pi$  GENIE model tune for MicroBooNE, Phys. Rev. D **105**, 072001 (2022), arXiv:2110.14028 [hep-ex].
- [11] A. Filkins *et al.* (MINERvA Collaboration), Double-differential inclusive charged-current  $\nu_\mu$  cross sections on hydrocarbon in minerva at  $\langle E_\nu \rangle \sim 3.5$  GeV, Phys. Rev. D **101**, 112007 (2020).
- [12] K. Abe *et al.* (T2K Collaboration), Improved constraints on neutrino mixing from the t2k experiment with  $3.13 \times 10^{21}$  protons on target, Phys. Rev. D **103**, 112008 (2021).
- [13] J. Nieves, I. R. Simo, and M. J. V. Vacas, Inclusive charged-current neutrino-nucleus reactions, Phys. Rev. C **83**, 045501 (2011).
- [14] L. Alvarez-Ruso *et al.* (GENIE), Recent highlights from GENIE v3, Eur. Phys. J. ST **230**, 4449 (2021), arXiv:2106.09381 [hep-ph].
- [15] J. Nieves, J. E. Amaro, and M. Valverde, Inclusive quasielastic charged-current neutrino-nucleus reactions, Phys. Rev. C **70**, 055503 (2004).
- [16] S. Kovalenko, Quasielastic neutrino production of charmed baryons from the point of view of local duality, Sov. J. Nucl. Phys. **52**, 934 (1990).
- [17] A. Pais, Weak interactions at high energies, Annals of Physics **63**, 361 (1971).
- [18] C. Berger and L. M. Sehgal, Lepton mass effects in single pion production by neutrinos, Phys. Rev. **D76**, 113004 (2007), [Erratum-ibid. D **77**, 059901(E) (2008)], arXiv:0709.4378 [hep-ph].
- [19] A. Bodek and U. Yang, Modeling deep inelastic cross sections in the few GeV region, Nucl. Phys. B (Proc. Suppl.) **112**, 70 (2002).
- [20] M. A. G. Aivazis, W.-K. Tung, and F. I. Olness, Next-to-leading order QCD formulation of deep inelastic scattering, in *Proceedings, The Vancouver Meeting, Particles & Fields'91: Vancouver, Canada, August 18–22, 1991* (1991) pp. 663–665, arXiv:hep-ph/9302305 [hep-ph].
- [21] T. Yang, C. Andreopoulos, H. Gallagher, K. Hoffmann, and P. Kehayias, A hadronization model for few-GeV neutrino interactions, Eur. Phys. J. C **63**, 1 (2009), arXiv:0904.4043 [hep-ph].
- [22] C. Andreopoulos *et al.*, The GENIE Neutrino Monte Carlo Generator: Physics and User Manual (2015), arXiv:1510.05494 [hep-ph].
- [23] J. L. Alcaraz-Aunion and J. Walding (SciBooNE), Measurement of the nu(mu)-CCQE cross-section in the SciBooNE experiment, AIP Conf. Proc. **1189**, 145 (2009), arXiv:0909.5647 [hep-ex].
- [24] V. Lyubushkin *et al.* (NOMAD), A Study of quasi-elastic muon neutrino and antineutrino scattering in the NOMAD experiment, Eur. Phys. J. C **63**, 355 (2009), arXiv:0812.4543 [hep-ex].
- [25] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), First measurement of the muon neutrino charged current quasielastic double differential cross section, Phys. Rev. D **81**, 092005 (2010), arXiv:1002.2680 [hep-ex].
- [26] A. A. Aguilar-Arevalo *et al.*, First measurement of the muon anti-neutrino double-differential charged-current quasielastic cross section, Physical Review D **88**, 10.1103/physrevd.88.032001 (2013).
- [27] K. Abe, J. Amey, C. Andreopoulos, L. Anthony, *et al.* (The T2K Collaboration), Characterization of nuclear effects in muon-neutrino scattering on hydrocarbon with a measurement of final-state kinematics and correlations in charged-current pionless interactions at t2k, Phys. Rev. D **98**, 032003 (2018).
- [28] D. Ruterbories *et al.* (MINERvA Collaboration), Measurement of quasielastic-like neutrino scattering at  $\langle E_\nu \rangle \sim 3.5$  GeV on a hydrocarbon target, Phys. Rev. D **99**, 012004 (2019).
- [29] X.-G. Lu, M. Betancourt, T. Walton, *et al.* (MINERvA Collaboration), Measurement of final-state correlations in neutrino muon-proton mesonless production on hydrocarbon at  $\langle e_\nu \rangle = 3$  GeV, Phys. Rev. Lett. **121**, 022504 (2018).
- [30] T. Cai *et al.* (MINERvA), Nucleon binding energy and transverse momentum imbalance in neutrino-nucleus reactions, Phys. Rev. D **101**, 092001 (2020), arXiv:1910.08658 [hep-ex].
- [31] P. Abratenko *et al.* (MicroBooNE Collaboration), First measurement of differential charged current quasielastic-like  $\nu_\mu$ -Argon scattering cross sections with the MicroBooNE Detector, Phys. Rev. Lett.

- 125**, 201803 (2020), arXiv:2006.00108 [hep-ex].
- [32] P. Abratenko *et al.* (MicroBooNE Collaboration), Measurement of differential cross sections for  $\nu_\mu$ -Ar charged-current interactions with protons and no pions in the final state with the MicroBooNE detector, Phys. Rev. D **102**, 112013 (2020), arXiv:2010.02390 [hep-ex].
- [33] M. F. Carneiro *et al.* (MINERvA), High-Statistics Measurement of Neutrino Quasielasticlike Scattering at 6 GeV on a Hydrocarbon Target, Phys. Rev. Lett. **124**, 121801 (2020), arXiv:1912.09890 [hep-ex].
- [34] D. Ruterbories *et al.* (MINERvA), Simultaneous measurement of proton and lepton kinematics in quasielastic-like  $\nu_\mu$ -hydrocarbon interactions from 2 to 20 GeV (2022), arXiv:2203.08022 [hep-ex].
- [35] P. Abratenko, M. Alrashed, R. An, *et al.* (MicroBooNE Collaboration), Measurement of differential cross sections for  $\nu_\mu$ -Ar charged-current interactions with protons and no pions in the final state with the microboone detector, Phys. Rev. D **102**, 112013 (2020).
- [36] C. E. Patrick *et al.* (MINERvA Collaboration), Measurement of the muon anti-neutrino double-differential cross section for quasielastic-like scattering on hydrocarbon at  $E_\nu \sim 3.5$  GeV, Phys. Rev. D **97**, 052002 (2018).
- [37] X.-G. Lu *et al.*, Measurement of nuclear effects in neutrino interactions with minimal dependence on neutrino energy, Phys. Rev. C **94**, 015503 (2016).
- [38] K. Abe, C. Andreopoulos, M. Antonova, *et al.* (T2K Collaboration), Measurement of double-differential muon neutrino charged-current interactions on  $c_8h_8$  without pions in the final state using the t2k off-axis beam, Phys. Rev. D **93**, 112012 (2016).
- [39] A. S. Meyer *et al.*, Deuterium target data for precision neutrino-nucleus cross sections, Phys. Rev. D **93**, 113015 (2016), arXiv:1603.03048 [hep-ph].
- [40] R. Gran, Model uncertainties for valencia rpa effect for minerva (2017).
- [41] P. A. Rodrigues *et al.* (MINERvA), Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer, Phys. Rev. Lett. **116**, 071802 (2016), [Addendum: Phys.Rev.Lett. 121, 209902 (2018)], arXiv:1511.05944 [hep-ex].
- [42] S. Dolan, G. D. Megias, and S. Bolognesi, Neutrino-nucleus scattering in the susa model, Phys. Rev. D **101**, 033003 (2020).
- [43] R. Freedman, G. Miller, and E. Henley, ISOBAR DYNAMICS AND PION NUCLEUS ELASTIC SCATTERING, Nucl. Phys. A **389**, 457 (1982).
- [44] E. J. Moniz, I. Sick, R. R. Whitney, J. R. Ficenec, R. D. Kephart, and W. P. Trower, Nuclear Fermi momenta from quasielastic electron scattering, Phys. Rev. Lett. **26**, 445 (1971).
- [45] O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Spectral function of finite nuclei and scattering of geV electrons, Nuclear Physics A **579**, 493 (1994).
- [46] S. Dytman, Y. Hayato, R. Raboanary, J. T. Sobczyk, J. Tena-Vidal, and N. Vololoniaina, Comparison of validation methods of simulations for final state interactions in hadron production experiments, Phys. Rev. D **104**, 053006 (2021).
- [47] J. Chakrani, M. Buizza Avanzini, and S. Dolan, Parametrising CCQE uncertainties in the Spectral Function model for neutrino oscillation analyses, PoS NuFact2021, 235 (2022), arXiv:2202.03219 [hep-ph].
- [48] T. Bonus, J. T. Sobczyk, M. Siemaszko, and C. Juszczak, Data-based two-body current contribution to the neutrino-nucleus cross section, Physical Review C **102**, 10.1103/physrevc.102.015502 (2020).
- [49] K. M. Hanson *et al.*, Probabilistic interpretation of peelle's pertinent puzzle and its resolution (2005).
- [50] G. D'Agostini, On the use of the covariance matrix to fit correlated data (1993).
- [51] A. Buckley *et al.*, Systematic event generator tuning for the LHC, Eur. Phys. J. C **65**, 331 (2010), arXiv:0907.2973 [hep-ph].
- [52] A. S. Meyer, A. Walker-Loud, and C. Wilkinson, Status of lattice qcd determination of nucleon form factors and their relevance for the few-gev neutrino program (2022), arXiv:2201.01839 [hep-lat].
- [53] K. Niewczas and J. T. Sobczyk, Nuclear transparency in monte carlo neutrino event generators, Phys. Rev. C **100**, 015505 (2019).
- [54] S. Dolan, Exploring Nuclear Effects in Neutrino-Nucleus Interactions Using Measurements of Transverse Kinematic Imbalance from T2K and MINERvA (2018), arXiv:1810.06043 [hep-ex].
- [55] G. Garino *et al.*, Proton propagation in nuclei studied in the (e,e'p) reaction, Phys. Rev. C **45**, 780 (1992).
- [56] T. O'Neill *et al.*, A-dependence of nuclear transparency in quasielastic a(e, e'p) at high q2, Physics Letters B **351**, 87 (1995).
- [57] D. Dutta *et al.*, Quasielastic (e, e'p) reaction on  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ , and  $^{197}\text{Au}$ , Phys. Rev. C **68**, 064603 (2003).
- [58] D. Rohe *et al.* (E97-006 Collaboration), Nuclear transparency from quasielastic  $^{12}\text{C}(e, e'p)$ , Phys. Rev. C **72**, 054602 (2005).
- [59] A. Ershova *et al.*, Study of final-state interactions of protons in neutrino-nucleus scattering with INCL and NuWro cascade models (2022), arXiv:2202.10402 [hep-ph].
- [60] A. Nikolakopoulos, R. González-Jiménez, N. Jachowicz, K. Niewczas, F. Sánchez, and J. M. Udías, Benchmarking intra-nuclear cascade models for neutrino scattering with relativistic optical potentials (2022), arXiv:2202.01689 [nucl-th].
- [61] L. Aliaga *et al.* (MINERvA Collaboration), Design, calibration, and performance of the MINERvA detector, Nucl. Instrum. Meth. A **743**, 130 (2014), arXiv:1305.5199 [physics.ins-det].
- [62] X. G. Lu *et al.* (MINERvA), Exploring neutrino-nucleus interactions in the GeV regime using MINERvA, Eur. Phys. J. ST **230**, 4243 (2021), arXiv:2107.02064 [hep-ex].
- [63] D. Michael, P. Adamson, *et al.*, The magnetized steel and scintillator calorimeters of the minos ex-

- periment, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **596**, 190 (2008).
- [64] D. Ruterbories *et al.* (MINER $\nu$ A Collaboration), Measurement of quasielastic-like neutrino scattering at  $\langle E_\nu \rangle \sim 3.5$  GeV on a hydrocarbon target, Phys. Rev. D **99**, 012004 (2019), arXiv:1811.02774 [hep-ex].
- [65] R. Acciarri *et al.*, Noise characterization and filtering in the MicroBooNE liquid argon TPC, Journal of Instrumentation **12** (08), P08003.
- [66] C. Adams *et al.*, Ionization electron signal processing in single phase LArTPCs. part II. data/simulation comparison and performance in MicroBooNE, Journal of Instrumentation **13** (07), P07007.
- [67] R. Acciarri *et al.* (MicroBooNE), The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector, Eur. Phys. J. C **78**, 82 (2018), arXiv:1708.03135 [hep-ex].
- [68] P. Abratenko *et al.* (MicroBooNE Collaboration), First measurement of inclusive muon neutrino charged current differential cross sections on argon at  $E_\nu \sim 0.8$  GeV with the microboone detector, Phys. Rev. Lett. **123**, 131801 (2019).
- [69] P. Abratenko, M. Alrashed, R. An, *et al.* (MicroBooNE Collaboration), First measurement of differential charged current quasielasticlike  $\nu_\mu$ -argon scattering cross sections with the microboone detector, Phys. Rev. Lett. **125**, 201803 (2020).
- [70] C. Adams *et al.* (The MicroBooNE Collaboration 1), First measurement of  $\nu_\mu$  charged-current  $\pi^0$  production on argon with the microboone detector, Phys. Rev. D **99**, 091102 (2019).
- [71] A. Bodek and T. Cai, Removal energies and final state interaction in lepton nucleus scattering, The European Physical Journal C **79**, 10.1140/epjc/s10052-019-6750-3 (2019).
- [72] E. S. P. Guerra *et al.*, Using world  $\pi^\pm$ -nucleus scattering data to constrain an intranuclear cascade model, Phys. Rev. D **99**, 052007 (2019).