SIST 2020: Single Transverse Variables in MicroBooNE

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A set of three observables, Single Transverse Variables (STVs), which characterise the kinematic imbalance of the final products generated from neutrino-nucleus interactions, are reconstructed using Monte Carlo simulations of the MicroBooNE detector. The method of using STVs to probe nuclear effects in neutrino-carbon interactions has succeeded in providing useful constraints on theoretical models. Due to the larger nucleon number, nuclear effects are expected to be even more important for understanding neutrino-argon scattering. This might lead to large systematic errors in argon-based neutrino oscillation measurements if the nuclear effects are not well-understood. In this study, we examine our reconstruction methods using two different theoretical predictions of differential cross sections with respect to the STVs. Some potential for discrimination between these two competing models is seen, but improvements to the analysis are needed to enable a full cross section measurement.

I. INTRODUCTION

A. Neutrino Oscillation Experiment

The study of neutrino oscillations is associated with several core problems at the frontier of particle physics. Current and future studies of neutrino oscillations will target the possible existence of leptonic CP violation, improve our knowledge of neutrino mixing parameters, and contribute to the effort to determine the neutrino mass ordering. The phenomenon of neutrino oscillation is described as the tendency of a neutrino to change flavor after traveling for a finite distance. The following equation quantifies the probability of a neutrino to oscillate away from its original flavor:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2(\frac{\Delta m^2 L}{4E})\,. \qquad (1)$$

Here α and β are neutrino flavors, θ is the mixing angle, Δm^2 is the squared mass splitting between state ν_α and ν_β, E is neutrino energy, and L is the traveling distance of the neutrino. Neutrino energy E cannot be observed directly in the experiment, which makes event reconstruction essential in the study of neutrino oscillations. Precise measurements of the neutrino oscillation probability are highly dependent on the accuracy of reconstructed neutrino energy. In the event reconstruction process, the neutrino energy is inferred from an observed event topology by using detector simulation in tandem with an event generator. The event rate with a given observable topology can be expressed as: [1]

$$N(\Theta) \propto \Phi(E_\nu)\sigma(E_\nu)P_{\nu\alpha\to\nu\beta}(E_\nu)\epsilon(E_\nu) \qquad (2)$$

where E_ν is the reconstructed energy, Φ is the incoming neutrino flux, σ is neutrino interaction cross section, P is the oscillation probability, and ϵ is the detector efficiency. From equation (2), it is clear that a detailed understanding of neutrino interaction cross-sections, the unoscillated flux and the detector response are crucial to reliably measure the neutrino oscillation probability. In this study, we focus on cross sections for neutrino scattering on an argon target.

B. Cross-Section Measurements

It is well-known that an accurate theoretical model of neutrino-nucleus interaction is essential for precise neutrino oscillation analyses. Typically, theoretical uncertainties on neutrino-nucleus cross section models are a leading source of systematic error. This is generally due to the difficulty of modeling nuclear effects in complex nuclei, such as the case of argon. Only a limited number of cross-section measurements are available for neutrino-argon interactions. Therefore, new cross-section measurements will play an important role in advancing our understanding of neutrino-argon interactions. This particular project pursues a "fake measurement" study where the results of Monte Carlo simulations are used to examine the event reconstruction process and our current analysis framework. Specifically, we reconstruct differential cross sections from simulated events in bins of Single Transverse Variables (STVs), a set of observables which account for the kinematic imbalance of the final-state particles. These variables have been employed previously by neutrino scattering experiments like MINERvA and T2K to study nuclear effects. There the focus was on neutrino-carbon interactions. By applying this technique from the investigation of carbon nuclei to the study of neutrino scattering on an argon target, we seek to obtain a more in-depth understanding of neutrino-nucleus scattering.

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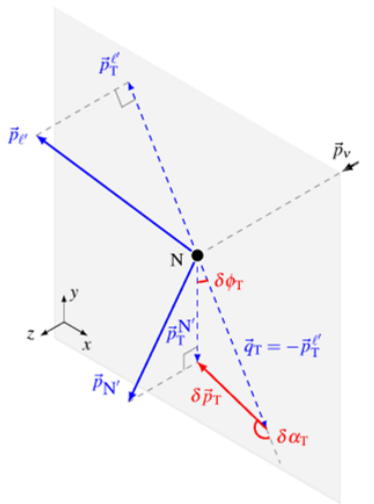

FIG. 1. Schematic presentation of Single Transverse Variables

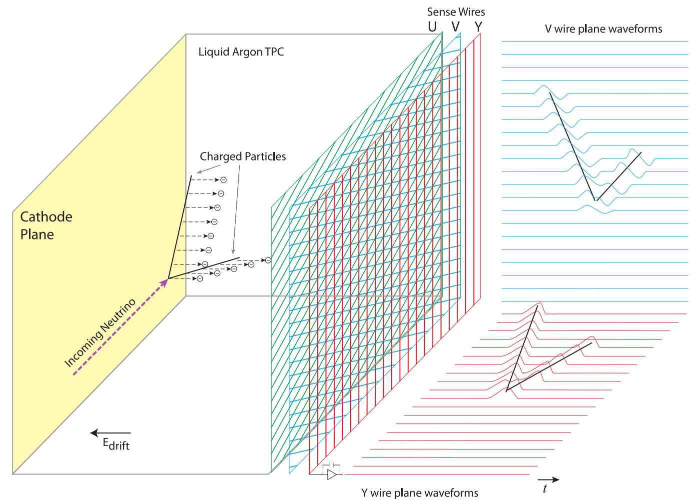

FIG. 2. Liquid Argon Time Projection Chamber

C. Single Transverse Variables

In the endeavor of making measurements of nuclear effects with a minimal dependence on the neutrino energy, Single Transverse Variables (STVs) are a set of three observables that are used to interpret the momentum of outgoing products detected in the final state of a neutrino-nucleus interaction. They are defined on a “transverse plane” which is oriented perpendicular to the direction of the incoming neutrino. The following equations define the three STVs: [1]

$$\delta p_T = \mid \delta \vec{p}_T \mid \equiv \mid \vec{p}_\mu^T + \vec{p}_p^T \mid \tag{3}$$

$$\delta\phi_T \equiv \arccos \frac{-\vec{p}_\mu^T \cdot \vec{p}_p^T}{p_\mu^T p_p^T} \tag{4}$$

$$\delta\alpha_T \equiv \arccos \frac{-\vec{p}_\mu^T \cdot \delta\vec{p}_T}{p_\mu^T \delta p_T} \,. \tag{5}$$

Here $\vec{p}_\mu^T$ and $\vec{p}_p^T$ are the momentum of the outgoing muon and of the leading proton projected on the transverse plane, respectively. The leading proton is the proton which possesses the highest momentum out of many protons detected in the final state of a neutrino-nucleus interaction. The distributions of STVs studied in this project are those seen for the “CC0πNp” event topology: a charged-current interaction that produces one muon, zero pions, and at least one proton at the final state. δp_T is the overall momentum imbalance of the muon and the leading proton. If the nucleon is free and at rest in the initial state, δp_T becomes 0. $\delta\phi_T$ is the angular transverse imbalance measured the angle between $-p_\mu^T$ and the direction of δp_T. In figure 1, $-\vec{p}_\mu^T = \vec{q_T}$, the transverse component of $\vec{q}$. The value of $\delta\alpha_T$ reflects whether the proton final-state interactions are accelerating or decelerating. $\delta\alpha_T$ is the angle between δp_T and $\vec{q_T}$. Together, all three of these observables provide a sensitive probe of nuclear effects.

D. The MicroBooNE LArTPC

The MicroBooNE detector is currently the longest-running LArTPC experiment in a neutrino beam, having started operations in October 2015. This detector carries 85 tons of liquid Argon and receive the neutrino source from Fermilab’s Booster Neutrino Beam (BNB) which locate 463 meters from the target. More than 90% of neutrino from BNB are ν_μ. The basic structure of the LArTPC is shown in Fig.2. The detector is contained within a cylindrical cryostat, where charged particles traversing a volume of highly-purified liquid Argon leave trails of ionisation in their wake. The traversing of charged particles in the same time also create prompt vacuum ultraviolet scintillation photons. Ionisation electrons are then detected by a system of anode wires in three planes, and scintillation photons are observed by a 32 photo-multipliers tube (PMT) located behind them. Data from PMT are also used to trigger the detector and to enhance rejection of cosmic-ray background. Measurements with detector medium Argon is of growing interest because it is promising to provide data which is significantly crucial for the study of nuclear effect in neutrino scattering. LArTPC is advantageous in neutrino oscillation experiments for being capable of producing high-resolution image of particles interactions. MicroBooNE is pursuing high-statistics measurements of neutrino-Argon cross sections. In our study, as previously mentioned, we use cross-section data as the constraint to improve neutrino-Argon theoretical model which efficiently extracts neutrino properties parameters from oscillation probability measurements. This will be substantially helpful in reducing systematic error in obtaining neutrino oscillation measurements with high accuracy for the case of complex nuclei as Argon.

II. METHOD

A. Data Samples

1. *Event selections*

CC0πNp event topology is selected to be the signal definition in this project. "CC" stands for "charged current" in charged-current neutrino scattering measurement, in which only outgoing charged lepton is taken into consideration irrespective of any other final-state particles. This type of interaction is typically being selected for the study of extracting oscillation probability parameters as the topology sets the stepping stone for any further investigations relevant to neutrino-nuclei interactions. Specifically, CC0π is the type of CCincl (CC inclusive) topology events that are dominantly represented in MicroBooNE experiments, provided their ability to yield out high statistic data with low background noises. In this study, we present the cross-section analysis of Charged Current events with one muon and N (where N is at least 1) proton in the final state. Selection of CC0πNp events has to also meet the following criteria:

- Magnitude of the outgoing μ's momentum is greater than 0.15 GeV
- Magnitude of the leading proton's momentum is greater than 0.3 GeV
- Exclude all the events that produce neutral pion in the final state
- All charged pions produced in the final state has the momentum less than 0.07 GeV

At neutrino energies between 0.1 and 1.5 GeV, CCQE interactions are fundamental way which neutrino interact with matters. CCQE interaction mode in this project is described as the following:

$$\nu_\mu + n \rightarrow \mu^- + p \tag{6}$$

Besides CCQE, some true events generated are also in the mode of Resonance Scattering (RES), Meson Exchange Current (MEC), and Deep Inelastic Scattering (DIS).

- Resonance Scattering (RES): neutrino interaction that results to a Δ or N* which may decay to produce pion in the final state.
- Meson Exchange Current (MEC):processes in which neutrino interacts with a correlated pair of nucleons.
- Deep Inelastic Scattering (DIS): processes in which neutrino interacts with a subcomponent of a nucleon instead of the nucleon as a whole.

All of the interactions described above are parts of Final State Interactions (FSI). FSI is a process of nuclear effects, which refers to all the interaction inside the nucleus before ejected hadrons escape from the nucleus. The complexity of FSI usually results from inelastic or elastic scattering and charge exchanges of particles within the nucleus. These interactions could involve the hadrons re-interact inside the nuclear medium where they could be absorbed, hadrons have their kinematics altered or they could stimulate additional nuclear emission. FSI are very challenging to model or constraint with experimental data. The attempt of using STV in this study is in the hope to shed light to the study of the nuclear effect in neutrino-argon interaction.

2. *GENIE Event Generator*

GENIE is an event generator which based on Monte Carlo simulation . GENIE is used to stimulate the physic processes taking place when a neutrino is scattered off a nuclear target. The generator employs validated models that describe fundamental physics processes in neutrino scattering, nuclear effects including the production of hadronic multiparticle as well as hadronic re-interactions. Gevgen is a generic GENIE event generation application for simple event generation cases. This application handles the case in which neutrinos scattered off a given target, in this case, Argon. It handles mono-energetic flux neutrinos. Two sets of events, each includes 10^6 events, are created using GENIE v3.0.6 from gevgen with tunes: `G18_10a_02_11a` (default model) and `G00_00b_00_000` (alternate model). Below are the description of interaction models implemented in each model set.

1. Events generated using tune `G18_10a_02_11a` (default model)
    - Nuclear model: Local Fermi Gas (LFG) model.
      It is helpful to get nucleon initial state momenta known as they give the boost to events of neutrino-nucleus interaction in the lab-frame. Models that are purposely designated to distribute those momenta are called spectral function models, and LFG is one of them. LFG is a specific type of a simple and commonly used 'relativistic Fermi gas' in which nucleons are considered as non-interacting fermions inside a pervading nuclear potential. LFG uses local density $\rho(r)$ and takes into account the dependence of nuclear potential on

the radial position of a nucleon within the nucleus (r) under the local density approximation to build up the spectra function model.

- CCQE: Nieves
- CCMEC: Nieves
- CCRES: Berger-Sehgal
- FSIs: GENIE hA2018.

2. Events generated using tune `G00_00b_00_000` (alternate model)

   - Nuclear model: Relativistic Fermi gas with "Bodek-Ritchie tail"
     This specific 'Relativistic Fermi gas' spectra function model include high momentum distribution from two nucleon correlations.
   - CCQE: Llewellyn-Smith
   - CCMEC: GENIE Empirical
   - CCRES: Berger-Sehgal
   - FSIs: GENIE hA.

3. Uboonecode reconstruction simulation

Uboonecode is a software which belongs to LArSoft [2], a toolkit for simulation, reconstruction and analysis of Liquid Argon Time Projection Chamber. It is designed specifically for the use of MicroBooNE data. Different from events generated from GENIE, events generated from uboonecode are in reconstructed space and are ready to be analyzed to obtain the data of our interest. In this study, we generated two sets of reconstructed events from uboonecode. One event set is created using the default model, and the other one is created using alternate model. Data extracted from uboonecode reconstructed events serve as the sample of fake measurement data. Specifically, interpretation of data in reconstructed space will be compared to fake measurement data from uboonecode.

B. Event reconstruction

1. Forward-Folding process

Fake data measurements are made for the purpose of ensuring the cross-section extraction method is unbiased and prone to reduce systematic errors. Investigation on fake data helps providing parameter extraction with plausible results on a wide range of real data scenarios. In the case where there is hardly any measurements available such as the cross-sections measurements of neutrino scattering in MicroBooNE, fake data study is a fundamental step that will ultimately enable appropriate interpretation on real data. However, theory data simulation can not be directly compared to measurement data due to numerous factors from resolution effects. A mitigation matrix is constructed to translate theory events into those that could be treated as data from experiments. The process in which mitigation matrix is transformed into a set of fake measurement data is called Forward- Folding process. The matrix is conventionally called "smearing matrix" because they take the responsibility to "smear" theoretical event distributions to observed event distributions by integrating the average detector response into the set of simulated events. In this study, the smearing matrix is built upon reconstructed event from uboonecode default model. Figure 3 shows an example of smearing matrix calculated for δp_T. It is computed as the following equation:

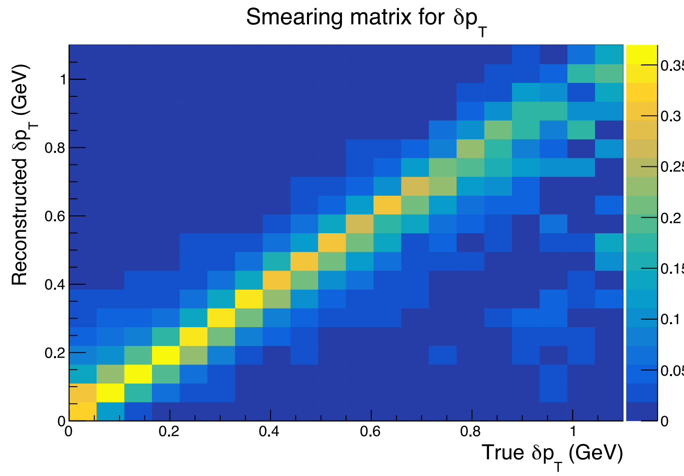

FIG. 3. Smearing matrix of δp_T

$$\nu_i = \sum_{j=1}^{M} S_{ij}\mu_j \tag{7}$$

where S is given by:

$$S_{ij} = P(\text{observed in bin } i \mid \text{true value in bin } j) \tag{8}$$

with ν_i and μ_j are numbers of events in the reconstructed bin i and the true bin j, respectively.

2. Extraction of Cross-Section parameters

We extract differential cross-section data as a function of variables (e.g: δp_T) from reconstructed event distributions using the following equation:

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N_i - B_i}{\tilde{\epsilon}\cdot N_{target}\cdot \Phi_{\nu_\mu}\cdot (\Delta x)_i} \tag{9}$$

where N_i is the total number of selected data events, B_i is the number of selected events that are not contributed

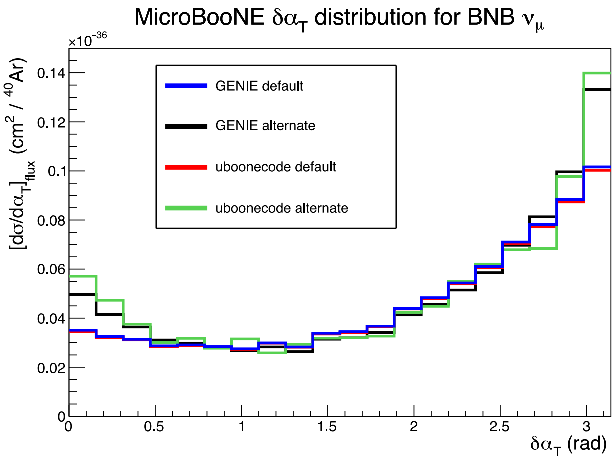

FIG. 4. Cross-section data for $\delta\alpha_T$

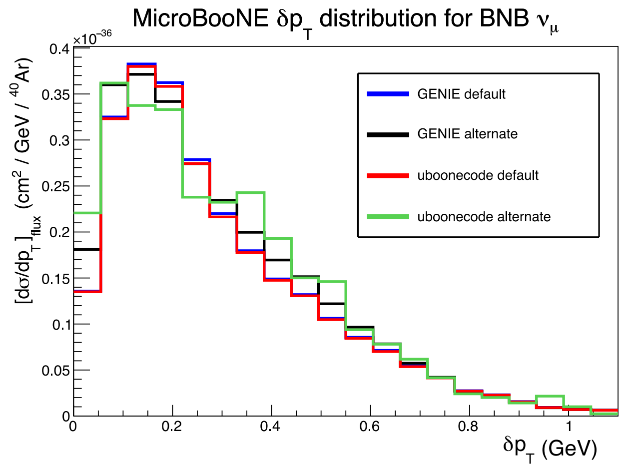

FIG. 6. Cross-section data for δp_T

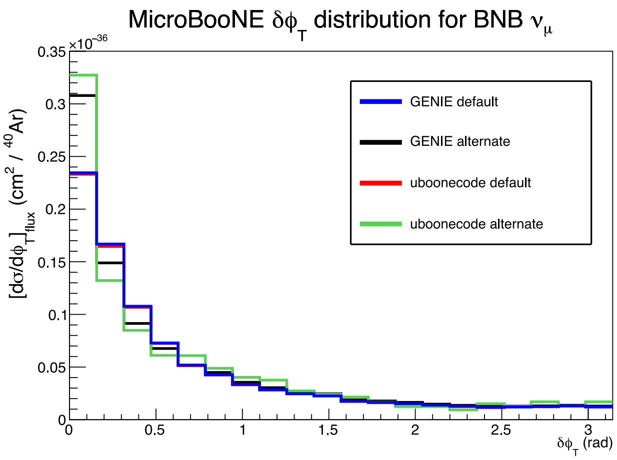

FIG. 5. Cross-section data for $\delta\phi_T$

to the signal, N_{target} is the number of argon atoms in the fiducial volume, Φ_{ν_μ} is the muon neutrino flux integrated and scaled to the corresponding protons-on-target (POT).

$\tilde{\epsilon}$ is the new efficiency which can be calculated as a function of the reconstructed quantities:

$$\tilde{\epsilon} = \frac{\sum_{j=1}^{M} S_{ij} N_j^{sel}}{\sum_{j=1}^{M} S_{ij} N_j^{gen}} \quad (10)$$

where N_j^{sel} is the number of signal selected events in true bin j, and N_j^{gen} is the number of generated events in true bin j.

III. RESULTS

This section shows the first preliminary results for the fake measurement study of cross-section measurement data in MicroBooNE. The first subsection is to discuss about the reliability of our computed smearing matrix. The second subsection discusses about the divergence of truth cross-section data from the two GENIE theory models that we implemented in the study. The last subsection gives an overview of the analysis on our reconstruction proceeding.

A. Closure Check

Data obtained from events belong to uboonecode default model is used to establish a smearing matrix. True cross-section data obtained from the two sets of events generated by GENIE is then operated by this smearing matrix to have data presented in the reconstructed space. As previously mentioned, this whole process if called forward- folding process. It is imperative to check the accurate level of the procedure that we used to compute the smearing matrix. The reliability of the smearing matrix operation used is expressed by the agreement between the cross-section data obtained after the forward-folding process is applied to the truth data extracted from events that belong to GENIE default model, and the cross-section data obtained from events that belong to uboonecode default model. This has shown on all three of our plotting results for $\delta\phi_T$, $\delta\alpha_T$, and p_T distribution.

B. Model Discrimination

The study features two different theory event sets, each with different modeling modes of neutrino interactions. Both of them attempts to have an accurate simulation of processes happening in neutrino scattering experiment with argon target. In figure 7, it is clear that the truth cross-section data obtained from GENIE default and al-

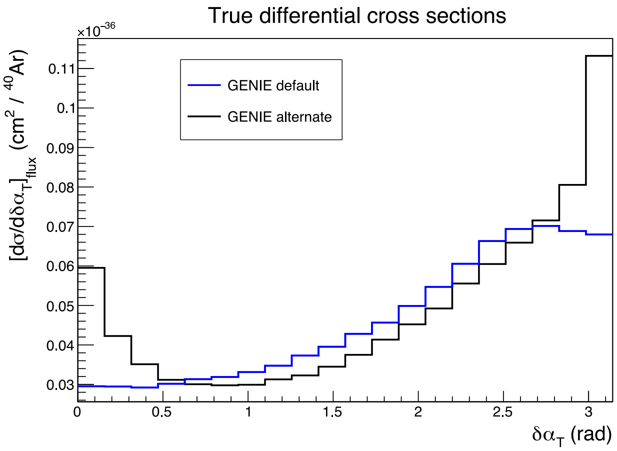

FIG. 7. Truth Cross-section data for $\delta\alpha_T$

ternate model in the bin of $\delta\alpha_T$ is significantly different. This is what we had expected to see when choosing the tuning when we started to generate events from GENIE. After the smearing matrix is applied to both of the truth cross-section data sets, the data displayed in the plotting result of $\delta\alpha_T$ distributions (Figure 4) and $\delta\phi_T$ distributions (Figure 5) shows that there is the discrimination between the smeared-data obtained from GENIE default model and from GENIE alternate model. The discrimination is more distinguishable at the high region of $\delta\alpha_T$ distribution, and the low region of $\delta\phi_T$ distributions. This result suggests that the physics underlie our smearing matrix is interesting enough for our further analysis.

C. Examine The Analysis Method

This study shows our attempt to test out the two model sets that have all the potential characterizations applicable to interpret real measurement data from MicroBooNE. The reliability of our event reconstruction method and our current analysis that we used to obtain cross-section data in the binning of STVs is evaluated by how well the smearing matrix operates on our truth data sets. For this "fake measurement" study, the ultimate goal is to compare how well could our forward-folding process match the smeared cross-section data obtained from GENIE alternate model events to the data obtained from uboonecode alternate model reconstructed events. Throughout all of our plotting results for all three STVs, there is no agreement shown between the data obtained from the two models mentioned. It is then obvious that the smearing matrix has introduced some biases into our analyses. In the high region of $\delta\alpha_T$ distributions (Figure 4) as well as in the low region of $\delta\phi_T$ distributions, the proximity between data from the two alternate models shows acceptable bias of the smearing matrix as the difference of the two data signal is small compare to the difference between the signal which indicates the data obtained from uboonecode default and uboonecode alternate reconstructed events. In the low region of δp_T distribution (Figure 6), however, the bias is really large as the difference between data from the two alternate models is comparable to the data results from uboonecode reconstructed events. This is the reason that we do not look at the binning at the low region for δp_T distributions in the analysis for model discrimination. Although there is sign of model discrimination shown in the plot of δp_T, the dominance of the bias that we have just discussed takes away the reliability of the smearing matrix applied for the case of δp_T distributions.

IV. CONCLUSION

This project presents the first fake data measurement study of cross-section mesurements of three Single Transverse Variables in MicroBooNE. Although the smearing matrix shows some dependence towards the default model from which it is originally built, it demonstrates the capability to discriminate cross-section measurement data extracted from the two theory events in the reconstructed space. The results show in the plot of δp_T suggests that some improvements on the reconstruction process are needed. There could be some underlying physics that we shall explore. Taking it further from here, a combination of refinement of bin choices, event selections, cross section binning, signal definition and reconstruction method will be pursued in the future.

[1] T2K collaboration, *Probing Nuclear Effects at the T2K Near Detector Using Transverse Kinematic Imbalance*, in *Prospects in Neutrino Physics*, 4, 2016, 1605.00179.

[2] E. Snider and G. Petrillo, *LArSoft: toolkit for simulation, reconstruction and analysis of liquid argon TPC neutrino detectors*, *Journal of Physics: Conference Series* **898** (2017) 042057.

[3] MicroBooNE collaboration, *Recent Neutrino Cross Section Measurements from MicroBooNE*, *PoS* **LeptonPhoton2019** (2019) 065.