PROCEEDINGS OF SCIENCE

Semi-inclusive charged-current neutrino-nucleus reactions: Analysis of data in the Relativistic Plane-Wave Impulse Approximation

J.M. Franco-Patino,[a,b,*] **M.B. Barbaro,**[b,c] **J.A. Caballero**[a,d] **and G.D. Megias**[a,e]

[a] *Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Reina Mercedes s/n, 41080 Seville, Spain,*

[b] *Dipartimento di Fisica, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*

[c] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*

[d] *Instituto de Física Teórica y Computacional Carlos I, Granada 18071, Spain*

[e] *Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*

E-mail: jfpatino@us.es, barbaro@to.infn.it, jac@us.es, megias@us.es

Semi-inclusive neutrino-nucleus cross sections within the plane-wave impulse approximation (PWIA) for three nuclear models: relativistic Fermi gas (RFG), independent-particle shell model (IPSM) and natural orbitals shell model (NO) are compared with the available CC0π measurements from the T2K, MINERνA and MicroBooNE collaborations where a muon and at least one proton were detected in the final state. Results are presented as a function of the momenta and angles of the final particles, as well as in terms of the imbalances between proton and muon kinematics. The analysis reveals that contributions beyond PWIA are crucial to explain the experimental measurements and that the study of correlations between final-state proton and muon kinematics can provide valuable information on relevant nuclear effects such as initial state dynamics and final state interactions.

**** The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021) ****
**** 6–11 Sep 2021 ****
**** Cagliari, Italy ****

*Speaker

Nuclear effects in neutrino-nucleus scattering are one of the main sources of uncertainty in the analysis of neutrino oscillation experiments. At present most of these studies have been focused on inclusive scattering processes where only the scattered lepton is detected in the final state. This implies, due to the extended neutrino energy distribution (flux), that very different reaction mechanisms can contribute to the cross section. Hence the determination of the neutrino energy, required in the analysis of neutrino oscillations, presents a high uncertainty due to effects associated to the nuclear dynamics.

In this context, one way to significantly improve the reconstruction of the neutrino energy together with the experimental systematic uncertainties is the analysis of more exclusive processes where selection criteria are also placed on the particle content of the hadronic system; i.e., in addition to the final lepton as in purely inclusive measurements, other particles are also detected. For example, this is the case of semi-inclusive events in which the lepton is detected in coincidence with one hadron in the final state. Accordingly, the T2K [1], MINERνA [2, 3], and MicroBooNE [4, 5] collaborations are each performing measurements of topologies involving one charged lepton detected in coincidence with one or more particles in the final state. In [6] we presented a detailed description of these processes using different nuclear models within PWIA. Although being aware of the oversimplified description of the reaction provided by PWIA, the comparison with experimental data presented in this work is meant to be a first step towards a more complete modeling and a useful benchmark for more sophisticated calculations that might include final state interactions (FSI) and contributions beyond the impulse approximation.

In PWIA, the neutrino-nucleus fifth-differential cross section factorizes into two terms: one corresponds to the weak interaction of the neutrino with a single nucleon of the nucleus and the other one the nuclear spectral function $S(p_m, E_m)$ that contains all the information about the nuclear dynamics. Taking into account that the neutrinos are distributed according to an energy distribution $P(k)$, then

$$\left\langle \frac{d\sigma}{dk' d\cos\theta_l dp_N d\Omega_N^L} \right\rangle = \frac{(G_F \cos\theta_c k' p_N)^2 m_N}{8\varepsilon' E_N (2\pi)^5} \int_0^\infty dk \frac{P(k)}{k} \upsilon_0 \mathcal{F}_\chi^2 S(p_m, E_m) \,, \tag{1}$$

with υ_0 a kinematic factor and $\mathcal{F}_\chi^2$ the reduced single nucleon cross section given in Appendix A of [6]. From the characteristic spectral function of each nuclear model it is possible to obtain the momentum distribution $n(p_m)$ of the nucleons inside the nucleus by integrating over the missing energy, E_m,

$$n(p_m) = \int_0^\infty dE_m S(p_m, E_m) \,, \tag{2}$$

which must be correctly normalized to the number of interacting nucleons, i.e. the number of neutrinos for charged-current neutrino scattering or the number of protons for antineutrinos scattering

$$\mathcal{N} = \frac{1}{(2\pi)^3} \int_0^\infty dp_m p_m^2 n(p_m). \tag{3}$$

The momentum distributions for the three nuclear models considered in this work, namely relativistic Fermi gas (RFG), independent-particle shell model (IPSM) [7] and natural orbitals shell model (NO) [8], are given in Fig. 1 (left picture) for ^{12}C.

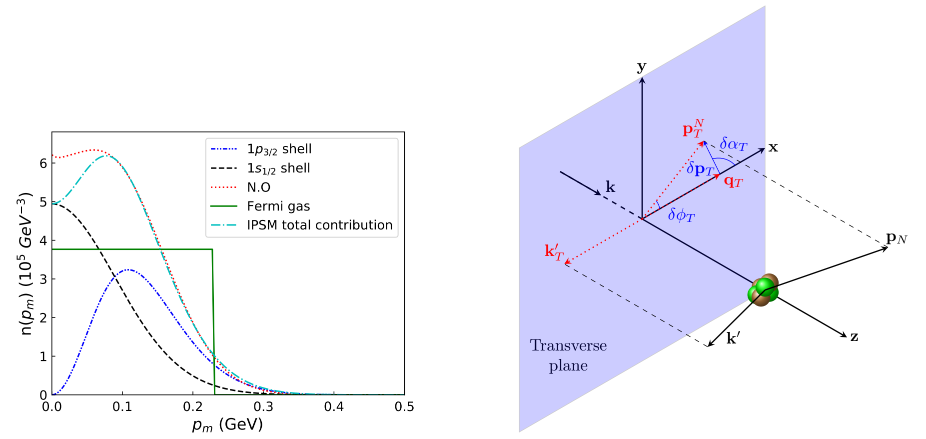

Figure 1: Left: Momentum distributions of neutrons normalized according to Eq. (3) for ^{12}C for the nuclear models considered in this work: RFG, IPSM and NO. The contributions of the different shells for the IPSM are also included. Right: Scheme showing the transverse kinematic imbalances (TKI): δp_T, $\delta\alpha_T$ and $\delta\phi_T$. The final lepton ($\mathbf{k}'$) and nucleon ($\mathbf{p_N}$) momenta are projected on the plane perpendicular to the neutrino ($\mathbf{k}$) direction (xy-plane or transverse plane). The transverse component of the transferred momentum ($\mathbf{q_T}$) equals to $-\mathbf{k}'_\mathbf{T}$ and defines the x-axis.

Instead of defining the semi-inclusive cross section as function of the final lepton and nucleon momenta and angles, we could use another set of variables, like the transverse kinematic imbalances (TKI) [9], that are especially designed to enhance some nuclear effects, and therefore discriminate between different nuclear models, with minimal dependence on the neutrino energy. The TKI require the detection in coincidence of the final lepton and the ejected nucleon and are defined by projecting the final lepton and the ejected nucleon momenta on the plane perpendicular to the neutrino direction as can be seen in Fig. 1 (on the right). More specifically, the vector magnitude of the momentum imbalance (δp_T) and the two angles ($\delta\alpha_T$ and $\delta\phi_T$) are:

$$\delta p_T = \left|\mathbf{k}'_T + \mathbf{p}_T^N\right|, \quad \delta\alpha_T = \arccos\frac{-\mathbf{k}'_T \cdot \delta\mathbf{p}_T}{k'_T \delta p_T}, \quad \delta\phi_T = \arccos\frac{-\mathbf{k}'_T \cdot \mathbf{p}_T^N}{k'_T p_T^N}, \tag{4}$$

where $\mathbf{k}'_T$ and $\mathbf{p}_T^N$ are, respectively, the projections of the final lepton and nucleon momenta on the transverse plane. In the PWIA, for which $\mathbf{k}' + \mathbf{p}_N = \mathbf{k} + \mathbf{p}_m$, $\delta\mathbf{p}_T$ is the transverse component of the initial nucleon momentum and $\delta\alpha_T$ the angle between the transverse projections of the initial nucleon momentum and the transferred momentum $\mathbf{q}$. Also, in absence of FSI, the $\delta\alpha_T$ distribution is expected to be flat.

In Fig. 2 we present CC0π1p results in PWIA compared with MicroBooNE and T2K data as function of muon and proton kinematics for RFG, IPSM and NO nuclear models. As shown, the uncertainty connected with the nuclear model is, in general, small and comparable with the one obtained for inclusive cross sections. In general, the interpretation of the discrepancies and agreements between our results and the data shown is not straightforward since the measured cross sections are affected by multiple initial and final nuclear state effects which cannot be easily separated in the momentum and angular kinematic distributions.

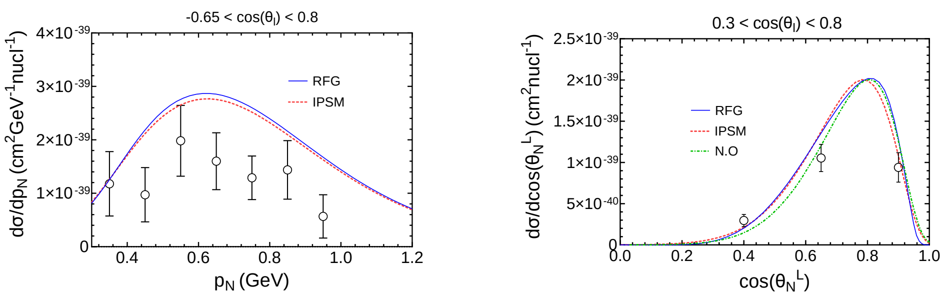

Figure 2: MicroBooNE [4] (ν_μ - ^{40}Ar left) and T2K [1] (ν_μ - ^{12}C right) semi-inclusive cross sections as function of muon and proton kinematics for different nuclear models. Figure adapted from [10].

In Fig. 3 we show the semi-inclusive cross section as function of TKI compared with MINERνA data. The δp_T distribution for the RFG model differs strongly from the other two, not only in magnitude and position of the maximum, but also in the fact that the RFG distribution vanishes for $\delta p_T > k_F$ as consequence of the Fermi condition. Although the position of the peak looks correct for the IPSM and NO models, the corresponding results overestimate the data in the low δp_T area (below the Fermi momentum located around 0.23 GeV/c for ^{12}C) and underestimate the data for high δp_T, indicating that effects beyond PWIA might be essential to describe correctly the data. Looking at the $\delta\alpha_T$ distribution on Fig. 3, the NO prediction is a bit greater than the RFG and IPSM ones, but all models exhibit a flat distribution as it was expected due to the PWIA and the isotropy of the associated momentum distributions. As it happened with δp_T, for $\delta\alpha_T$ and $\delta\phi_T$ we also see that PWIA is inadequate to describe the data. Finally, for the cross section as function of δp_{Ty} the results in the PWIA are able to reproduce correctly the position of the peak but fail to match the long tails appreciated in the experimental data and also overestimate some of the data around the peak. Contributions beyond PWIA may reduce the discrepancies observed in the present analysis.

Conclusions

Semi-inclusive neutrino-nucleus reactions where a muon and one proton are detected in the final state can be used, with the right selection of experimental observables, to identify relevant nuclear effects related to both the initial state dynamics and to FSI, as well as to two-particle-two-hole excitations and thus improve the reconstruction of the neutrino energy. The PWIA is an oversimplification of such complex processes, although it is a good starting point that highlights the importance of contributions beyond the PWIA necessary for the correct description of the available experimental data. Work is in progress to extend the present analysis to include FSI based on the Relativistic Mean Field approach.

Acknowledgments

This work received funding from the Spanish Ministry of Science, Innovation and Universities and ERDF under contract FIS2017-88410-P and PID2020-114687GB-100, by the Junta de Andalucía

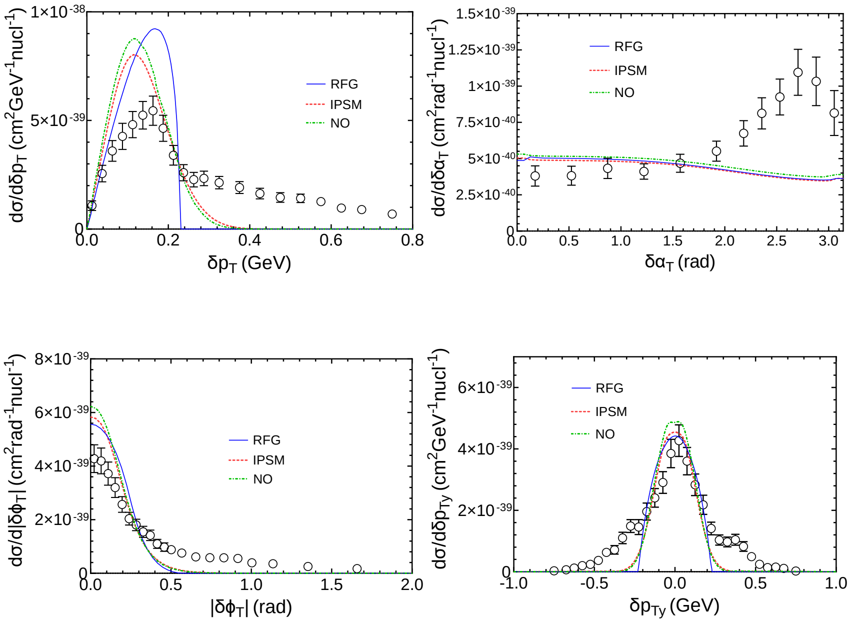

Figure 3: MINERνA [3] ν_μ - ^{12}C semi-inclusive cross section as function of TKI for different nuclear models. The variable δp_{Ty} is the projection in the y-axis of the imbalance δp_T. Figure adapted from [10].

(grants No. FQM160, SOMM17/6105/UGR and P20_01247), by the INFN and the University of Turin, by the European Unions Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 839481 and by University of Tokyo ICRR's Inter-University Research Program FY2020 and FY2021.

References

[1] K. Abe *et al* (The T2K Collaboration), Phys.Rev. D **98**, 032003 (2018)

[2] X.-G *et al* (MINERνA Collaboration), Phys.Rev. Lett **121**, 022504 (2018)

[3] T. Cai *et al* (MINERνA Collaboration), Phys.Rev. D **101**, 092001 (2020)

[4] P. Abratenko *et al* (MicroBooNE Collaboration), Phys.Rev. D **102**, 112013 (2020)

[5] P. Abratenko *et al* (MicroBooNE Collaboration), Phys.Rev. Lett **125**, 201803 (2020)

[6] J.M. Franco-Patino *et al*, Phys.Rev. C **102**, 064626 (2020)

[7] J. W. Van Orden and T. W. Donnelly, Phys.Rev. C **100**, 044 (2019)

[8] M. V. Ivanov *et al*, Phys.Rev. C **89**, 014607 (2014)

[9] X.-G. Lu *et al*, Phys.Rev. C **94**, 015503 (2016)

[10] J.M. Franco-Patino, M.B. Barbaro, J.A. Caballero and G. D. Megias, Phys.Rev. D **104**, 073008 (2021)