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Inelastic neutrino-nucleus scattering in the superscaling model

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Charged-current inclusive neutrino cross sections on ^{12}C and ^{40}Ar target are analyzed using the susperscaling model SuSAv2, for the first time extended to the full inelastic region. The model contains two new ingredients: the first is a scaling function used to describe the Δ resonance region, built after subtracting from (e, e') experimental cross sections the quasielastic, two-particle two-hole, higher resonances and deep inelastic scattering (DIS) contributions arising from the SuSAv2-MEC model [1]; the second is the description of the resonance and DIS regimes through the extension to the neutrino sector of the SuSAv2-inelastic model already available for (e, e') reactions, which combines phenomenological structure functions with a nuclear scaling function. Two different options for the description of the Δ region are presented and discussed. The results of the model are tested against (e, e') data and inclusive neutrino cross-section measurements from the T2K and ArgoNEUT experiments, thus covering several kinematical regions.

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1. Introduction

In recent neutrino experiments, there are numerous mechanisms that contribute to the nuclear response. Theoretical analyses have been developed to describe these contributions. The quasi-elastic regime can be reproduced by models like SuSAv2 [3]. Other channels like two-particle two-hole or the Δ resonance region have been studied within the same model. However, there is still a lack of knowledge regarding higher resonance and the deep inelastic scattering (DIS) regimes. In this study, neutrino interaction models for the inelastic regime are explored.

Inclusive charged-current (CC) neutrino-nucleus scattering cross sections have been measured in various experiments and at different energy regimes. In T2K, MicroBooNE or SciBooNE, the main contributions to the cross sections are quasielastic (QE), one pion (1π) production and two-particle two-hole (2p2h) meson-exchange current (MEC), being QE the dominant one [8]. Nevertheless, other experiments such as MINERvA, NOvA, ArgoNEUT or the forthcoming DUNE operate at higher kinematics, in which the inelasticities, like higher resonances (HR) or DIS, become more important [9]. Here we focus in the T2K and ArgoNEUT measurements.

In this work, we update and extend two models based on the SuperScaling Approach, the Relativistic Mean Field (RMF) ingredients included in the SuSAv2 model and an analysis of inclusive (e, e') data. First, we focus on the Δ resonance region and update our previous semi-phenomenological model for this region, which it is labeled as "SuSAv2-Δ". Second, we present an extension of the SuSAv2-inelastic for electrons [2] to the neutrino sector referred as "SuSAv2-inelastic".

2. Methodology

We use the so-called SuSAv2 model [3] which improves the original prescription (SuSA) by means of the RMF theory. This allows to build a more sophisticated theory-based approach that reproduces very well the superscaling behavior shown by electron scattering data while improving the description of the transverse channel. This model, which was originally developed for the QE regime, was extended to the Δ resonance region and to the full inelastic regime. This second case was only available for electrons until now [2].

In the SuSAv2-Δ model, we obtain a semi-phenomenological Δ scaling function to be used in the Δ resonance region. The latest version of SuSAv2-MEC (SuSAv2-QE and 2p2h model) is used to remove QE and 2p2h contributions from the data [1]. In a similar way, contributions beyond Δ resonance (HR + DIS) are removed by applying the SuSAv2-inelastic model. By this method we isolate Δ-resonance contributions from inclusive electron scattering experimental cross section:

$$\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{\Delta} = \left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{exp.\ data} - \left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{SuSAv2-QE} - \left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{2p2h} - \left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{HR+DIS} \quad (1)$$

and then dividing the result by the elementary $N \to \Delta$ cross section

$$f^{\Delta}(\psi_{\Delta}) = k_F \frac{\left(\frac{d^2\sigma}{d\Omega_e d\omega}\right)^{\Delta}}{\sigma_{Mott}(\upsilon_L G_L^{\Delta} + \upsilon_T G_T^{\Delta})}, \quad (2)$$

we obtain the semi-phenomenological scaling function.

As commented before, the SuSAv2-inelastic model, which is an extension of the SuSAv2-QE formalism to the complete inelastic spectrum - resonant, non-resonant and deep inelastic scattering-, originally developed for electron reactions [2] is here extended to the neutrino sector. The inelastic nuclear responses are obtained by integrating the nuclear responses depending on the final-state reduced invariant mass (μ_X) over all possible final hadronic states [3],

$$R_K^{inel}(\kappa,\tau) = \frac{N m_N^3}{k_F^3 \kappa} \xi_F \int_{\mu_X^{min}}^{\mu_X^{max}} d\mu_X \mu_X f^{model}(\psi_X) G_K^{inel}. \tag{3}$$

The limits of the integral vary depending on whether the Δ region is included or excluded. The factor G_K^{inel} includes three inelastic structure functions (F_1, F_2 and F_3) for neutrinos.

In electromagnetic interactions, the single-nucleon hadronic responses depend on the inelastic structure functions F_1 and F_2. In the region of moderate and large x-values, the neutrino inelastic structure functions can be related to the electromagnetic ones through [4]:

$$F_{1,2}^{\nu N} \approx \frac{18}{5} F_{1,2}^{eN}. \tag{4}$$

The additional structure function in weak interactions, i.e. F_3, can be written using the quark distributions [4],

$$xF_3^{\nu N} = x(d(x) + u(x) + s(x) + \bar{s}(x) - \bar{u}(x) - \bar{d}(x) - c(x) - \bar{c}(x)), \tag{5}$$

where $u(\bar{u})$, $d(\bar{d})$, $c(\bar{c})$ and $s(\bar{s})$ are the distributions for the up, down, charm and strange quarks (antiquarks), respectively. These approximations based on QCD theory are valid at high kinematics. Additionally, the proposal given by the Bodek-Ritchie parametrization [5] connects F_3 and F_2 by ,

$$xF_3^{\nu N} = F_2^{\nu N} - 2\bar{Q}(x), \tag{6}$$

where the antiquark distribution, $\bar{Q}(x)$, is defined in terms of empirical fits of electron scattering under some approximations. Both options are explored in our work.

3. Results

As a first step, we test the models for electrons. In Figure 1, we show the double differential inclusive cross section for electron-nucleus (^{12}C) scattering. In order to explain the experimental data it is necessary to consider all reaction channels, i. e., QE, 2p2h and inelastic contributions. The inelastic contributions are obtained using two methods: the SuSAv2-inelastic for the whole inelastic spectrum (Full inelastic) or the SuSAv2-Δ working alongside SuSAv2-inelastic for higher resonances and deep inelastic scattering (Δ + DIS), better for neutrinos due to the limitations of the structure functions. Furthermore, we also consider different parametrizations for the inelastic structure functions: Bodek-Ritchie (BR) [5], Bosted-Christy (BC) [6] or Parton Distribution Function (PDF) [7]. As it is observed in Figure 1, only the BC parametrization within the SuSAv2-inelastic model reproduces well the inelastic region. Similar results are observed using the SuSAv2-Δ model.

In T2K and ArgoNEUT experiments, the (anti)neutrino fluxes peak at 0.6 GeV and (3.6) 9.6 GeV, respectively. In both cases, the models reproduce well the experimental data at different kinematics, as seen in Figures 2 and 3. Notice that for ArgoNEUT, we notice that the DIS channel represents an essential contribution to the inclusive cross section, as expected at higher kinematics.

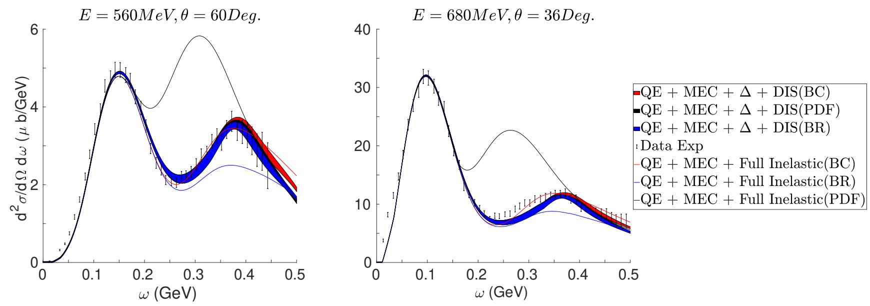

Figure 1: Double-differential inclusive cross section for $(e, e')^{12}C$ scattering at a given beam energy and scattering angle -labeled in the panels. It is displayed in function of the transferred energy.

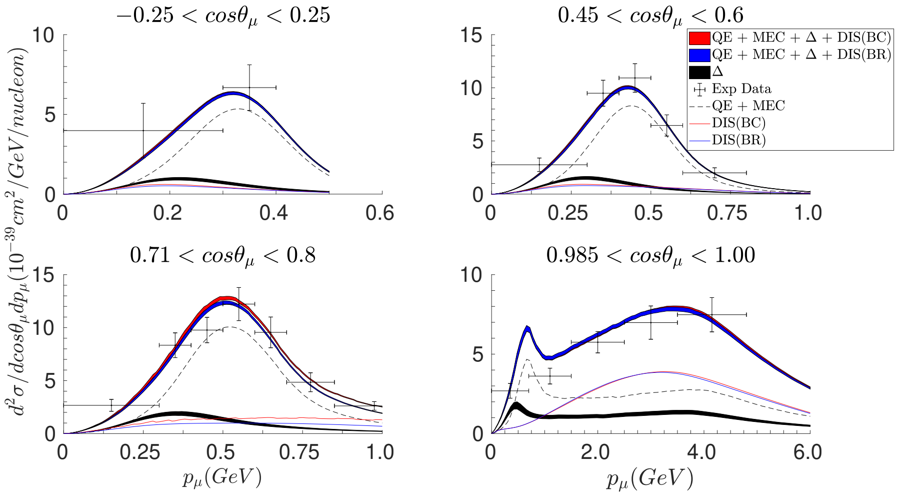

Figure 2: The CC-inclusive T2K flux-folded ν_μ-^{12}C double differential cross section per nucleon, for different bins in the muon scattering angle -labeled in the panels. It is displayed in function of the muon momentum. The data come from [8].

4. Conclusion

In conclusion, the addition of deep inelastic scattering and other inelastic channels is necessary to properly analyze neutrino scattering at high kinematics. This is relevant for current experiments like T2K and ArgoNEUT and it would be relevant for future DUNE and HK experiments. The two approaches presented here yield a reasonable agreement for electron and neutrino cross section measurements, providing promising alternatives to other approaches currently implemented in MC event generators. A more detailed publication about this issue is currently in preparation.

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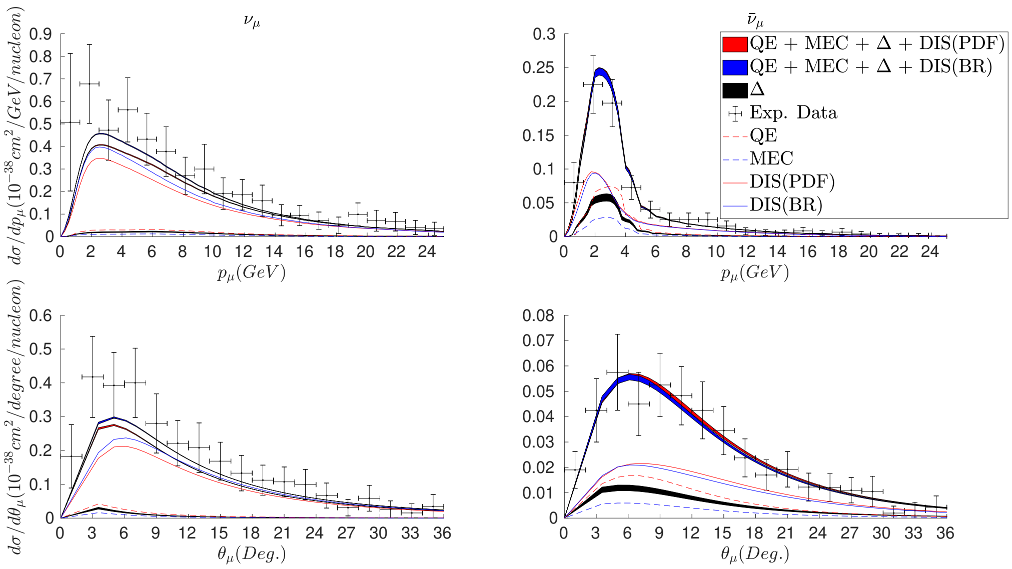

Figure 3: The CC-inclusive ArgoNEUT flux-integrated $\nu_\mu(\bar{\nu}_\mu)$-^{40}Ar single differential cross section per argon nucleon, displayed as function of the muon momentum (top) or the muon scattering angle (bottom). The data come from [9].

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