Comparison of predictions for nuclear effects in the Marteau model with the NUX+FLUKA scheme

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Nuclear effects in neutrino-nucleus reactions simulated by means of the NUX+FLUKA Monte Carlo generator are compared with the theoretical predictions of the Marteau model. Pion absorption in NUX+FLUKA and non-pionic Δ decays in the Marteau model differ by about 30%. The fraction of pions produced due to the re-interactions after primary quasi-elastic vertex is in the NUX+FLUKA scheme much higher than provided by the Marteau model.

1. INTRODUCTION

The aim of our investigation was to compare predictions for neutrino interactions provided by NUX+FLUKA Monte Carlo scheme [1] with those of the Marteau model [2]. We were interested mostly in nuclear effects in pion production but for completeness (and for the sake of checking normalization factors) we have also presented the results for the quasi-elastic reaction.

The motivation for this study can be summarized in the following points:

i) In recent years there has been growing interest in the studies of neutrino interactions at energies of a few GeV where the dominant contributions to the cross section come from quasi-elastic and single pion production channels [3].

ii) It is well known that the NUX+FLUKA MC scheme designed originally to describe neutrino interactions at higher energies is not satisfactory in a few GeV neutrino energy region [4]. It does not include separate resonance contribution implemented in alternative MC codes after Rein-Sehgal model [5].

iii) Developments in quark-hadron duality suggest that perhaps it is not necessary to include many resonances apart from the Δ excitation [6,7].

iv) The Marteau model describing together quasi-elastic and Δ production reactions on nuclear targets is an interesting candidate for implementation in MC codes. Its original version includes a contribution from 2 particles - 2 holes excitations. The model was a subject of further investigation [5] and it is important to understand if it is useful for practical applications.

v) On the purely theoretical side there are interesting questions concerning the way in which nuclear effects beyond Fermi gas model are taken into account. One way is to describe them numerically e.g. by FLUKA. An alternative is to perform sophisticated theoretical computations like RPA. It is important to compare predictions of these two approaches.

In this paper we confine ourselves to the CC reactions of muon neutrinos. The NUX+FLUKA Monte Carlo predictions were made by using the PRET driver. For the total cross sections plots a sample of $10^5$ events was produced for each neutrino energy value. The events were classified based on some primary vertex characteristics as well as the number of pions in the final state. The overall normalization factor for the cross section was taken from the PRET’s output file pre1.out.
Figure 1. The total cross section for the CC quasi-elastic $\nu_\mu$ scattering on free nucleon. The experimental points are taken from [9].

The differential cross section, i.e. the hadronic invariant mass distribution in the $\nu p \rightarrow \mu^- p \pi^+$ channel, was obtained from a sample of $10^6$ inelastic events with the neutrino energy fixed at 1GeV.

All the numerical predictions of the Marteau model are based on [5].

2. QUASI-ELASTIC REACTIONS

The total cross sections for CC quasi-elastic scattering on free nucleons are compared in Fig. 1. We find good agreement between the two plots. The small difference may be attributed to slightly different parameter values (e.g. axial mass) or to the approximation assumed in the Marteau model where the terms of order $\frac{|\vec{p}|}{M}$ ($\vec{p}$ is target nucleon momentum) are omitted from the hadronic tensor. In the detailed comparison of several MC codes predictions which was presented by Zeller during her NuInt02 talk [4] even bigger differences were shown.

The results for the scattering on the oxygen nucleus are shown in Fig. 2. The NUX+FLUKA events are classified based on the particles leaving the primary vertex and as a result the FSI is not taken into account. To be more specific for the plot of the CC quasi-elastic scattering cross section only events with proton and muon produced in the primary vertex are considered. On the other hand the plot for the Marteau model was obtained without the RPA corrections. In other words two free Fermi gas models are compared.

The difference between the plots seen in Fig. 2 has at least two reasons. Firstly it is inherited from the difference seen in Fig. 1. Secondly it can be caused by different distributions of the target nucleons momenta assumed in the two models. In the Marteau model a quadratic distribution with sharp cut at $k_F = 225 MeV$ is assumed while in the NUX+FLUKA event generator a smooth distribution is used [10].

To be able to compare theoretical predictions with experiment such nuclear effects as the reinteraction or the $\Delta \rightarrow NN$ channel must be taken into account.
The cross section for the CC $\nu_\mu$ quasi-elastic scattering on $^{16}$O (no pions in the final state). The contributions from pion absorption (NUX+FLUKA) and non-pion $\Delta$ resonance decays (Marteau model) are shown separately with the dotted lines.

The plots in Fig. 3 were obtained by using the particles seen in the final state to select the CC quasi-elastic scattering events. This means that in the NUX+FLUKA generated event the primary vertex might be classified as either quasi-elastic or single pion production but not only. However, we neglected rather small contributions from other primary vertex kinds because they are not included in the Marteau model. The plot obtained for the Marteau-Model includes RPA corrections.

The comparison of plots found in figures 2 and 3 leads to the conclusion that nuclear effects increase the cross section.

This increase comes from an extra contribution from pion absorption in the case of the NUX+FLUKA generator and from the non-pion decays of the $\Delta$ resonance in the case of the Marteau model. It is interesting that two contributions of so different origin are of the same order of magnitude.

The difference between these two corrections rises with the neutrino energy reaching about 30% at 2GeV and causes the cross-section produced by the NUX+FLUKA generator to be slightly higher than the one obtained in the Marteau model.

### 3. SINGLE PION PRODUCTION

Predictions for single $\pi$ production on free nucleons are compared only for the $\nu p \rightarrow \mu^- p \pi^+$ channel. In this channel most of pions are produced through $\Delta^{++}$ excitation. In the experimentally measured hadronic invariant mass distribution a resonance peak is clearly seen [11]. In the case of $\nu n \rightarrow \mu^- n \pi^+$ and $\nu n \rightarrow \mu^- p \pi^0$ channels the resonance peak is smeared out which indicates that the dynamics is more complicated.

In Fig. 4 we compare the total cross sections predicted by both models with the experimental points. While both curves agree roughly with the results of Barish [11], the data points from [12] seem to favour the Marteau model.

In Fig. 5 a similar comparison is made for the normalized hadronic invariant mass distributions.
Figure 5. Normalized invariant hadronic mass distribution in single $\pi^+$ production on free protons. See explanation in the text.

The neutrino energy has been fixed at 1 GeV in both models because the experimental points were taken from [11] where most of the events came from neutrinos of energy around 1 GeV. In order to compare only distribution’s shapes all the plots have been normalized to yield the same total cross section value (that of the Marteau model at neutrino energy 1 GeV). The shape obtained in the Marteau model agrees well with the data points which further justifies the hypothesis that most of the pions come from the $\Delta^{++}$ decay. The disagreement between the shape obtained from NUX+FLUKA event generator and the data points is not surprising in this context as it is known not to contain any explicit resonance contribution.

In the next two figures the total cross sections of the pion production on oxygen are presented. Contributions from all three pion production channels were added here because in the Marteau model they are related to each other by the isospin Clebsch-Gordan rules and they cannot be tested independently. In Fig. 6 we classified the events based on the particles leaving the primary vertex. There is a major disagreement between the two curves: NUX+FLUKA predicts cross section to be much higher than the one obtained from the Marteau model. At neutrino energy 2 GeV the difference is already by a factor of 2 and it is seen that in the Marteau model the cross section saturates at much lower energy. The two main reasons for this discrepancy are the following:

1) in the Marteau model pions are produced only via the $\Delta$ excitation with other (non-resonant, higher resonances) contributions neglected. Therefore the cross sections are underestimated.

2) as shown in [4] the NUX+FLUKA predictions in $\nu n \rightarrow \mu^- n \pi^+$ and $\nu n \rightarrow \mu^- p \pi^0$ channels are significantly overestimated.

In Fig. 7 the cross sections for single pion appearance in the final state are shown. Prediction of the Marteau model is again much lower. Analysis of [4] shows that already at neutrino energy 2 GeV NUX+FLUKA predict cross section higher than saturation plateau of approaches based on Rein-Sehgal model. By adding three contributions one can expect that the plateau should be at approximate value $10 \cdot 10^{-38} cm^2$. 
Finally we considered the fraction of pions that are produced due to the Final State Interactions. In Fig. 8 we show the predictions of both approaches. The value of this fraction obtained in the NUX+FLUKA scheme is four times larger then the one calculated in the Marteau model.

This big difference can be discouraging but it is instructive that questions like this can be posed and answered within both numerical and analytical frameworks.

We hope that the discussion about numerical and analytical approaches to the description of nuclear effects in neutrino interactions can lead to improvements in existing MC codes.

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