Simulations from a new neutrino event generator

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We construct a new Monte Carlo generator of events for neutrino interactions. The dynamical models for quasi-elastic reactions, $\Delta$ excitation and more inelastic events described by the DIS formalism with the PDFs modified according to recent JLab data are used. We describe in detail single pion production channels, which combine the $\Delta$ excitation and DIS contribution. Many comparisons of the outcome of simulations with experimental data are presented.

1. INTRODUCTION

We present a new Monte Carlo generator of events for neutrino interactions. The original motivation for our work was to improve NUX+FLUKA scheme where no separate resonance contribution is present [1]. The aim of NUX+FLUKA was to describe interactions of neutrinos of higher energies and from that point of view the resonance part was of minor importance. Usually MC generators contain a resonance contribution described by means of Rein-Sehgal model covering the kinematical region of hadronic invariant mass $M + m_\pi \leq W \leq 2\text{GeV}$. If for neutrino reactions the quark-hadron duality holds true one can assume that contributions from higher resonances are averaged by deep inelastic scattering (DIS) structure functions and that only the dominant $\Delta$ resonance has to be treated separately.

The current version of the generator includes various dynamical models: quasi-elastic [2], $\Delta$ excitation [3], and DIS for which we use GRV94 Parton Distribution Functions (PDF) [4] with modifications proposed by Bodek and Yang [5]. The total cross section for the neutrino scattering is assumed to be the incoherent sum:

$$\sigma_{\text{total}} = \sigma_{\text{QE}} + \sigma_{\text{SPP}} + \sigma_{\text{DIS}} + \sigma_{\text{CC}} + \sigma_{\text{NC}},$$

where $\sigma_{\text{SPP}}$ is the sum of cross sections for single pion production (SPP) and CC and NC denote charge and neutral current reactions respectively.

The MC generator is organized around the event structure which contains three vectors of particles: incoming, temporary and outgoing. It also contains a structure with all the parameters used and a set of boolean flags tagging the event as QEL, DIS, CC, NC etc. The input parameters are read at startup from a text file and the events are stored in the ROOT tree file to simplify further analysis. Different interactions are implemented as functions acting on the event structure reading the incoming particles and producing the temporary ones. The type of the interaction is chosen according to the ratio of the total cross sections.

In our presentation we focus on single pion channels. We present many comparisons with the existing experimental data. In the near future the generator will be supplemented with a module with nuclear effects.

2. FRAGMENTATION ALGORITHM

In our MC we use the DIS formalism to generate events in the whole kinematical region where inelastic reactions are possible. In order to get the event record for the final state we assume that interaction occurs always on a particular parton and then the fragmentation of interacting quark and spectator is performed by means of PYTHIA6 [6] routines.

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The inclusive cross section for the scattering off nucleon is given by
\[
\frac{d^2 \sigma^{\nu E \rightarrow \mu E}}{dx dy} = \frac{G_F^2 M E}{\pi} \left[ \left( \frac{xy^2}{2} + \frac{ym^2}{2ME} \right) F_1 (x, Q^2) + \left( 1 - y - \frac{M}{2E} \right)^2 \frac{m^2}{2ME} F_2 (x, Q^2) \right]
\]
\[
\pm \left( xy - \frac{xy^2}{2} - \frac{ym^2}{4ME} \right) F_3 (x, Q^2) \right]. \tag{2}
\]

Structure functions are assumed to be those defined in the parton model i.e. the combinations of a PDFs
\[
F_1 (x, Q^2) = \sum_j [q_j (x, Q^2) + \bar{q}_j (x, Q^2)]
\]
\[
F_3 (x, Q^2) = 2 \sum_j [q_j (x, Q^2) - \bar{q}_j (x, Q^2)] \tag{3}
\]
\[
F_2 (x, Q^2) = 2xF_1 (x, Q^2)
\]
Using structure functions the cross section is rewritten in terms of contributions from separate partons \(q_i\)
\[
\frac{d^2 \sigma^{\nu q_i \rightarrow \mu q_j}}{dx dy} \sim q_i K_i, \tag{4}
\]
where \(K_i\) is a kinematic factor for parton \(q_i\).

A probability of reaction on a given quark is:
\[
P(q_i) = \frac{d^2 \sigma^{q_i \rightarrow \mu q_j}}{d^2 \sigma^{q_i \rightarrow \mu q_j}} \sum_i \frac{d^2 \sigma^{q_i \rightarrow \mu q_j}}{d^2 \sigma^{q_i \rightarrow \mu q_j}} \tag{5}
\]

PYTHIA fragmentation routines require a system of quark and diquark and perform fragmentation and hadronization using the LUND algorithm. Depending on the interacting parton, we distinguish several cases [7]:

- In the case of the scattering off the valence quark, a string is formed from the created quark and the remaining diquark.
- In the case of scattering off a sea quark \(u\) or \(d\), the remaining anti-quark annihilates with appropriate valence quark, and the created quark forms a string with the the remaining diquark, exactly as in the previous case.
- If scattering off an anti-quark \(u\) gives an anti-quark \(d\) or scattering off an anti-quark \(d\) gives an anti-quark \(u\), the created parton annihilates with a valence quark.
Figure 3. CC cross section for $\nu N \rightarrow \mu^- X$ interaction. Total cross section is split into contributions from quasi-elastic, SPP ($W < 2$ GeV) and more inelastic processes. Data points are taken from [12], [13], [14], [15], [16].

Figure 4. CC cross section for $\bar{\nu}N \rightarrow \mu^+ X$ interaction. Total cross section is split into contributions from quasi-elastic, SPP ($W < 2$ GeV) and more inelastic processes. Data points are taken from [16], [17], [18], [19], [20], [21].

- If scattering off an anti-quark $u$ gives a strange anti-quark $s$ or scattering off an anti-quark $d$ gives an anti-quark $c$, it creates with one of valence quarks a strange or a charm meson and the remaining quarks form a string for the fragmentation.
- In the cases of scattering off a strange quark or anti-quark, the remaining strange constituent creates a strange meson with one of valence quarks and the remaining quarks form a string for the fragmentation.

We fine tuned the PYTHIA6 generator parameters of the fragmentation. In fig. (1) the comparison of the charged particles multiplicities

$$P(n_{ch}) = \sigma(n_{ch})/\sum_{n_{ch}} \sigma(n_{ch})$$

as obtained from our simulation with the data from the Fermilab bubble chamber [8] is shown.

3. 1-PION FUNCTIONS

The only resonance we consider is the $\Delta$ and we have to estimate the single pion production
Figure 6. Cross section for $\nu n \rightarrow \mu^- \pi^+ n$. For data points and for simulations only events with hadronic mass $W < 2$ GeV were included. Data points are taken from [12], [14], [15], [22].

Figure 7. Cross section for $\nu n \rightarrow \mu^- \pi^0 p$. For data points and for simulations only events with hadronic mass $W < 2$ GeV were included. Data points are taken from [12], [14], [15], [22].

Figure 8. Cross section for NC SPP channels. For data points and for simulations only events with hadronic mass $W < 2$ GeV were included. Data points are taken from [23].

cross section as a fraction of the inclusive DIS cross section extrapolated into the resonance region. This is done separately for each SPP channel and the obtained fractions are called 1-pion functions. They are the probabilities that in a given point in the kinematically allowed region the final state is that of SPP.

$$f_{SPP}(W, \nu) = \frac{d^2\sigma_{DIS-SPP}}{dWd\nu}$$

In our generator $f_{SPP}$ are reconstructed using the LUND fragmentation algorithm. They turn out to be functions of $W$ only and are shown in fig. (2). We see that up to the threshold for two pion production, 1-pion function for proton and the sum of functions for neutron are equal 1. In more common language 1-pion functions can be recognized as average elasticities of resonances $\Gamma_{N\pi}/\Gamma_{total}$ [9]. In fig. (2) we see that in fact the values of 1-pion functions are close to resonance elasticities in a wide range of hadronic invariant mass.
4. SINGLE PION PRODUCTION

Our model of SPP combines in a smooth way the \( \Delta \) excitation model with the SPP part of the DIS cross section. We choose a linear transition with respect to hadronic invariant mass \( W \in (1.3, 1.6) \text{ GeV} \). As a bonus we obtain an artificial resonance-like behavior of the cross section at \( W \sim 1.5 \text{ GeV} \) which closely resembles the contribution from the \( D_{13}, S_{11} \) resonances [10]. We describe the non-resonant background as a small admixture of the DIS SPP contributions at low values of \( W \). Our MC reproduces the following analytical expression for the cross section:

\[
\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^\Delta}{dW} (1 - \alpha(W)) + \frac{d\sigma^{DIS}}{dW} f^{SPP}(W)\alpha(W) \tag{8}
\]

where

\[
\alpha(W) = \Theta(1.3\text{GeV} - W) \frac{W - W_{th}}{W_{min} - W_{th}},
+ \Theta(W_{max} - W)\Theta(W - W_{min}) \frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}}
+ \Theta(W - W_{max})
\]

\( \alpha_0 \in (0, 0.3) \), depending on the channel. We note that a similar value for the division line in the hadronic invariant mass between resonance and DIS contributions \( (W^{DIS}_{cut} = W^{RES}_{cut} = 1.5 \pm 0.02) \) was found by Naumov et al. [11] by fitting procedure to the existing set of experimental data.

The performance of our generator is presented on a series of plots. First we show contributions to the inclusive cross section for neutrino and antineutrino interaction on isoscalar target (figs. 3-4) from three theoretically separated dynamical mechanism. The SPP contribution is restricted by a cut \( W \leq 2 \text{ GeV} \).

The cross sections for CC SPP channels are shown in figs. 5-7. We conclude that the agreement with the data is satisfactory. In fig. 8 we show the plots for NC SPP channels.

We also compared the distribution of events in hadronic mass for SPP channels with the data from the BNL experiment. It is an important test because our procedure of modelling SPP channels is different from what is done in other MC codes. We used the BNL neutrino beam and generated the same number of events as reported in [15]. The results are shown in figs. (8-10). In the case of neutrino-proton reaction the agreement is excellent. In the case of \( \nu n \rightarrow \mu^- \pi^0 p \) reaction the agreement is very good but our simulations give too high \( \Delta \) peak. In the case of \( \nu n \rightarrow \mu^- \pi^+ n \) there is an experimentally measured access of events with small invariant mass.
Figure 11. Distribution of events in hadronic mass for BNL experiment and predictions of our Monte Carlo for $\nu n \rightarrow \mu^{-}\pi^{0}p$

(smaller then $M_{\Delta} = 1232$ MeV) which is not reproduced by our simulations.

5. FINAL REMARKS

We find our results for SPP encouraging. An improvement in the $\nu n \rightarrow \mu^{-}\pi^{0}n$ channel can probably be achieved by a more accurate treatment of the non-resonant background.

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