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HADRON PRODUCTION IN WROCŁAW NEUTRINO EVENT GENERATOR*

Jarosław A. Nowak, Jan T. Sobczyk

Institute of Theoretical Physics, University of Wrocław
M. Borna 9, 50-204 Wrocław, Poland

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Results from the Wrocław Monte Carlo neutrino generator of events are reported. Predictions for charged hadron multiplicities, neutral pion and strange particle production are presented and compared with available data.

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1. Introduction

The aim of this paper is to present some details about the performance of the neutrino Monte Carlo generator of events developed at the Wrocław University. It differs from other generators (*e.g.* NEUGEN, NUANCE, NEUT) [1] in the treatment of the resonance region. Our generator contains an explicit Δ resonance excitation model but contributions from more massive resonances are absent. It is assumed that an average description of the cross section coming from those resonances is sufficient. In fact, in the low energy BNL data only the Δ peak is clearly seen in all single pion production (SPP) channels on free nucleon targets [2]. In neutrino interactions with nucleus targets the Fermi motion is supposed to average the cross section contributions from other then the Δ resonance peaks.

The performance of the Wrocław generator in the SPP channels has been discussed elsewhere [3]. The agreement with available data is satisfactory. In order to cover the entire allowed kinematical region it is necessary to apply the DIS formalism to produce the events also for values of invariant hadronic mass $W \leq 2$ GeV. Two problems arise then: *(i)* how to model the structure functions in order to reproduce the correct value of the inclusive cross section and *(ii)* how to produce the final states.

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The generally accepted way to describe the structure functions is to use Bodek–Yang low Q^2 modifications, which have been introduced on the basis of the electron scattering data [4]. Recently the neutrino scattering data from the CHORUS and NuTeV experiments on nuclear targets (iron and lead) have become available [5] and further progress and cross checks will be possible. In order to produce final hadronic states several strategies can be adopted. In our approach we assume that interactions take place on separate constituent of the nucleon. The first step of fragmentation is performed by our generator and of remaining quark–diquark system by means of PYTHIA6 routines based on the LUND model [6]. Several parameters of PYTHIA6 were fine-tuned to get a good agreement with data [7]. In effect it is possible to produce DIS events for small values of the invariant hadronic mass down to the threshold for the single pion production $W \geq W_{\rm thr} \equiv M + m_\pi$. The low W DIS events are used in order to model the non-resonant background [8].

The description of the whole generator is presented in [9]. In this paper we will present some details about the performance of generator's hadronization routines.

2. Results

Average multiplicities $\langle n_{\rm ch}\rangle$ of charged hadrons have been measured in several experiments and the typical dependence

$$\langle n_{\rm ch}\rangle = a + b\,\ln W^2/{\rm GeV}^2, \tag{1}$$

has been observed. In Ref. [10] (it contains a misprint in the value of a in (2)) the following fits have been found:

$$a \;=\; 0.50 \pm 0.08\,, \qquad b = 1.42 \pm 0.03\,, \qquad \text{for CC} \qquad \nu p \to \mu X^{++}, \tag{2}$$
$$a \;=\; -0.20 \pm 0.07\,, \qquad b = 1.42 \pm 0.03\,, \qquad \text{for CC} \qquad \nu n \to \mu X^{+}. \tag{3}$$

In the experiment [10] results for scattering off proton and neutron target were extracted from the Fermilab 15-foot deuterium bubble chamber data. Average neutrino energy was about 50 GeV and multiplicity distributions were studies in the invariant mass range $1 < W < 15$ GeV.

In the paper [12] quite different values of the parameter a nd b were found:

$$a = -0.05 \pm 0.11\,, \qquad b = 1.43 \pm 0.04\,, \qquad \text{for CC} \qquad \nu p \to \mu X^{++}. \tag{4}$$

In the experiment [12] multiplicities of hadrons were obtained from the hydrogen bubble chamber BEBC and the investigated range of the invariant hadronic mass was $3.5 < W < 10$ GeV.

The results from the Wrocław generator are shown in Fig. 1. It is seen that the average multiplicities are much lower then the data from [10] while agreement with data from [12] is very good. The difference between two measurements is probably due to rescattering inside deuterium [10]. We verified that very similar to ours results are produced by the original PYTHIA6 code.

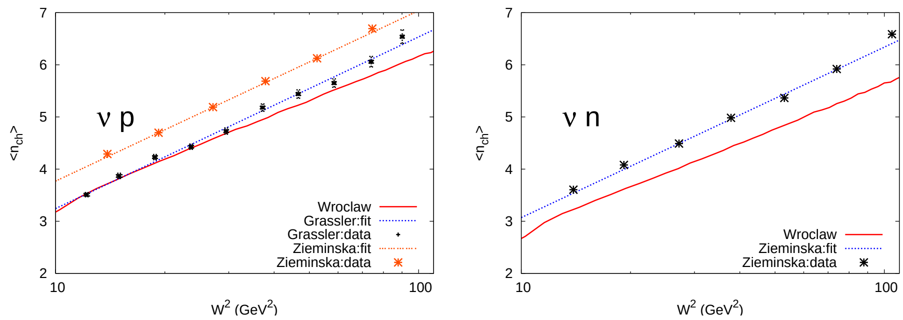

Fig. 1. Average charged hadron multiplicity in neutrino scattering off proton and neutron targets. Data points are taken from [10, 12].

The distribution of multiplicities agrees well with the KNO model and is independent of the value of W. It means that the probability to observe n charged hadrons is

$$f(n, \langle n_{\rm ch}\rangle) = F\left(\frac{n}{\langle n_{\rm ch}\rangle}\right), \tag{5}$$

where F is the universal scaling function.

In Fig. 2 the distributions of multiplicities obtained from the Wrocław generator are shown and compared with the data from [10]. We see that the pattern of distributions predicted by the MC generator agrees with the data but higher multiplicities are systematically underestimated as could be expected from the results for $\langle n_{\rm ch}\rangle$.

In Fig. 3 we show the average charged hadron multiplicities for antineutrino reactions.

The fits obtained in [11] are

$$a = 0.02 \pm 0.20\,, \qquad b = 1.28 \pm 0.08\,, \qquad \text{for CC} \qquad \bar{\nu}p \to \mu^+ X^0\,, \tag{6}$$

$$a = 0.80 \pm 0.09\,, \qquad b = 0.95 \pm 0.04\,, \qquad \text{for CC} \qquad \bar{\nu}n \to \mu^+ X^-\,. \tag{7}$$

The agreement of generator's predictions with the data is satisfactory.

It is also important to investigate NC reactions. Here the data is available with the average charged hadron multiplicities [16]:

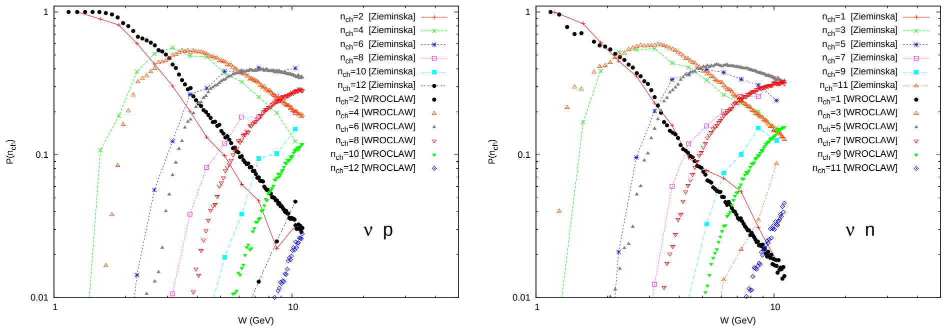

Fig. 2. Charged hadron multiplicities in neutrino scattering off proton and neutron targets. Data points are taken from [10].

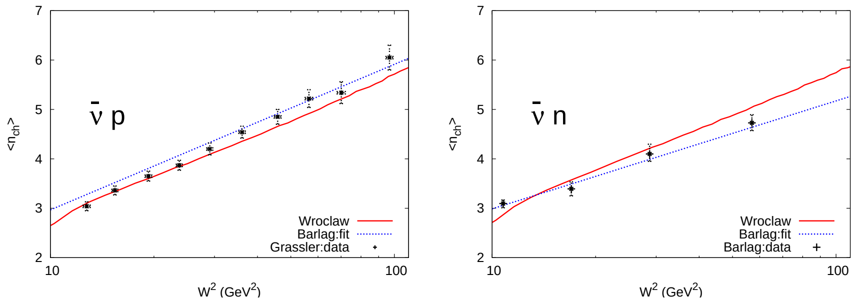

Fig. 3. Average charged hadron multiplicity in antineutrino scattering on proton and neutron. Data points are taken from [12] and the fit was found in [11].

$$a = 1.61 \pm 0.16\,, \qquad b = 0.99 \pm 0.05\,, \qquad \text{for NC} \qquad \nu p \to \nu X^+\,, \tag{8}$$

$$a = 1.65 \pm 0.20\,, \qquad b = 0.95 \pm 0.07\,, \qquad \text{for NC} \qquad \bar{\nu} p \to \nu X^+\,. \tag{9}$$

The comparison of MC predictions with the data is shown in Fig. 4 and the clear disagreement is seen. We were not able to obtain the original paper and data. The presented fits are taken from [16]. As far as we know the NC data was never published as an official WA21 Collaboration's paper.

We did not find the experimental data for charged pion multiplicities. One can use the existing data from anti-muon scattering and estimate the charged pion multiplicities in neutrino reactions but such reconstruction carries, especially for lower values of W, an uncertainty which is difficult to evaluate.

The precise data exists for neutral pion production on the proton target. They are again given in the form of a fit to the general formula (1):

$$a = 0.14 \pm 0.26\,, \qquad b = 0.50 \pm 0.08\,, \qquad \text{for CC} \quad \nu p \quad \pi^0 \text{ production}, \tag{10}$$

$$a = 0.17 \pm 0.42\,, \qquad b = 0.53 \pm 0.13\,, \qquad \text{for CC} \quad \bar{\nu} p \quad \pi^0 \text{ production}. \tag{11}$$

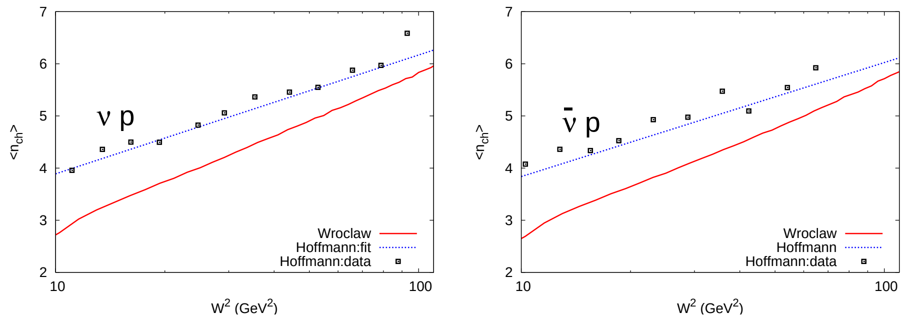

Fig. 4. Average charged hadron multiplicities in neutrino NC scattering off proton and neutron targets. Data points are taken from [16].

In Fig. 5 we show our MC predictions for π^0 production. The agreement with the data is excellent.

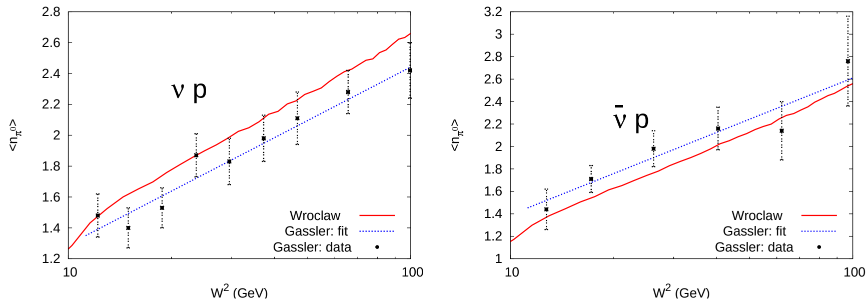

Fig. 5. Average neutral pion production multiplicities in neutrino and antineutrino scattering on proton. Data points are taken from Grässler *et al.* [12].

In Fig. 6 we show our generator's predictions for the ρ^0 production in νp and $\bar{\nu} p$ scattering. The data is taken from [13]. In the case of neutrino the agreement with data is satisfactory, but for anti-neutrino scattering the cross section for ρ^0 production is overestimated.

Another good test of the hadronization routines of the generator is provided by predictions for the strangeness production.

At low anti-neutrino energy strange particles can be produced in quasi-elastic processes but we do not discuss them here. In Fig. 7 the generator's predictions for the cross section for $\nu n \to \mu^- K^+ \Lambda$ reaction are shown. The data was taken from [14, 15] and it does not seem to be consistent (notice the log scale). The MC results are in general agreement with the data.

Finally, in Fig. 8 we show the cross section for neutral strange particles K^0 and Λ^0. Data points are taken from [17–20]. We notice the good agreement of the generator's predictions with the data.

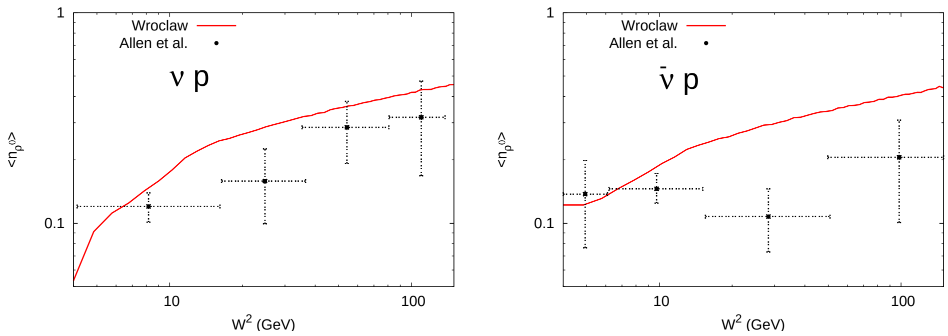

Fig. 6. Average ρ^0 production multiplicities in (anti-) neutrino scattering off proton. Data points are taken from [21].

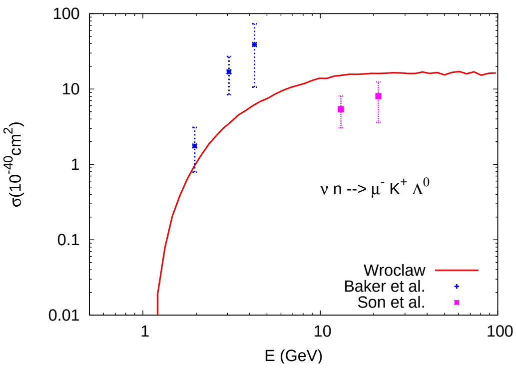

Fig. 7. Cross sections for channel $\nu n \to \mu^- K^+ \Lambda$. Data points are taken from [14, 15].

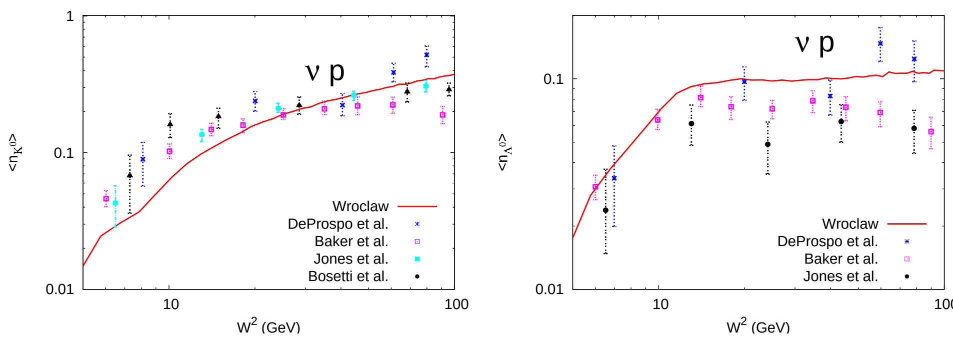

Fig. 8. Average neutral strange K^0 and Λ^0 particles multiplicity in neutrino scattering on proton.

3. Conclusions

The predictions of the Wrocław MC generator of events are in satisfactory agreement with the data. Nevertheless additional effort is necessary to fine tune some of the free parameters of the generator in order to improve its performance. The work on the nuclear effects module of the generator is in progress.

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REFERENCES

[1] Proceedings of the series of NuInt workshops: *Nucl. Phys. B (Proc. Suppl.)* **112**, (2002); *Nucl. Phys. B (Proc. Suppl.)* **139**, (2005).
[2] T. Kitagaki *et al.*, *Phys. Rev.* **D34**, 2554 (1986).
[3] C. Juszczak, J.A. Nowak, J.T. Sobczyk, `hep-ph/0512365`.
[4] A. Bodek, U.K. Yang, *Nucl. Phys. Proc. Suppl.* **112**, 70 (2002).
[5] `http://neutrinooscillation.org/`, `http://www-e815.fnal.gov/`
[6] T. Sjostrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).
[7] J.A. Nowak, to be published in *Physica Scripta T.*
[8] J.T. Sobczyk, J.A. Nowak, K.M. Graczyk, *Nucl. Phys. B (Proc. Suppl.)* **139**, 266 (2005).
[9] J.A. Nowak, PhD Thesis (in Polish), will be available at `http://wng.ift.uni.wroc.pl/theses.html`
[10] D. Ziemińska *et al.*, *Phys. Rev.* **D27**, 47 (1983).
[11] S. Barlag *et al., Z. Phys.* **C11**, 283 (1982).
[12] H. Grässler *et al., Nucl. Phys.* **B223**, 269 (1983).
[13] H. Grässler *et al., Nucl. Phys.* **B272**, 221 (1986).
[14] N.J. Baker *et al.*, *Phys. Rev.* **D24**, 2779 (1981).
[15] D. Son *et al.*, *Phys. Rev.* **D28**, 2129 (1983).
[16] E. Hoffman, Multiplicity in NC νp $\bar{\nu} p$ scattering, PhD Thesis cited in N. Schmitz, Hadron production in high-energy neutrino and anti-neutrino collisions, preprint MPI-PAE/Exp-El-193.
[17] N.J. Baker *et al., Phys. Rev.* **D34**, 1251 (1986).
[18] P. Bosetti *et al., Nucl. Phys.* **B209**, 29 (1982).
[19] D. DeProspo *et al., Phys. Rev.* **D50**, 6691 (1994).
[20] G.T. Jones *et al., Z. Phys.* **C57**, 197 (1993).
[21] P. Allen *et al.*, *Nucl. Phys.* **B194**, 373 (1982).