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Nucleon structure functions and UHE neutrino detectors

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Abstract. We have studied two topics of interest for UHE neutrino detection. First, with the goal to account for the uncertainty of the neutrino-nucleon cross section at ultra-high energy, we have estimated the influence of nuclear effects due to quark shadowing at small x. Secondly, we discuss the possibility of using UHE neutrino detectors to extract information on structure functions at low x and large Q^2, beyond the capacity of terrestrial accelerators.

1 Introduction

The high energy neutrino cross section is an essential ingredient for the calculation of the event rate expected in high energy neutrino telescopes from a variety of predicted neutrino fluxes (Gaisser, Halzen and Stanev, 1995; Bhattacharjee and Sigl, 2000). Detectors presently in design or construction stages (F. Halzen et al, 1995) look for Čerenkov light from the neutrino-induced muon in charged current interactions and take advantage of both the long muon range and the rise of the neutrino-nucleon cross section to meet the neutrino detection challenge.

The background of atmospheric muons is rejected searching for neutrinos that have travelled through the earth. For energies above a few hundred TeV the interaction length for neutrinos becomes comparable to the Earth diameter. As a result the event rate is a convolution of the differential spectrum, the cross section and the exponential attenuation of the neutrino flux. Uncertainties in the cross section get amplified into the energy spectrum and the angular distribution of the event rate and it is important that they are kept under control.

The DIS cross section is usually obtained from x and Q^2 dependent structure functions extracted from experimental data using the theoretical prediction in perturbative QCD given by the DGLAP evolution equations (Gribov and Lipatov, 1972; Lipatov, 1975; Altarelli and Parisi, 1977; Dokshitzer, 1977)

In the process of cross section calculation, it is necessary to compute parton densities (structure functions) in the x and Q^2 region without direct experimental support. One has to be specially cautious with the low x extrapolation due to the appearance of potentially large logarithmic terms that can break down the perturbative prediction. At the highest energies, uncertainties within 20% (Glück, Kretzer and Reya, 1999), 40% (Kwiecinski, Martin and Stasto, 1999) and a factor $2^{\pm 1}$ (Gandhi et al, 1998) are typically reported.

A different approach is provided by the BFKL formalism (Lipatov, 1976; Kuraev, Lipatov and Fadin, 1976; Balitzki and Lipatov, 1978; Lipatov, 1986) which deals with the Q^2 evolution of unintegrated in transverse momentum parton densities. The BFKL results are nowadays under discussion. the leading order prediction does not agree with data and the next-to-leading order result is found to be suspiciously large, although it seems that a reasonable value can be achieved by the adequate choosing of the renormalization scale (Brodsky et al, 1999).

In this letter we discuss another source of uncertainty in the calculation of the high energy neutrino-nucleon DIS cross section which comes from the fact that parton densities widely used were extracted under the assumption that partons belong to isolated nucleons when, on the contrary, the nucleons are usually bound in larger nuclei at the interaction sites. We compute below these effects by means of the modification of the standard parton densities in free nucleons to include nuclear effects following Eskola, Kolhinen and Salgado (1999).

2 Nuclear effects on $\sigma^{\nu(\overline{\nu})N}$

In terms of structure functions the charged-current (CC) neutrino-nucleon DIS differential cross section is given by:

$$\frac{d\sigma^{\nu(\overline{\nu})N}}{dxdy} = \frac{G_F^2\; M_W^4\; 2ME_\nu}{4\pi\;(M_W^2+Q^2)^2}\;(y_+F_2 - y^2F_L \pm y_-xF_3) \quad (1)$$

where $y_\pm = 1 \pm (1-y)^2$, M is the nucleon mass, E_ν the neutrino energy in the lab frame, $Q^2 = 2ME_\nu xy$ and terms suppressed by powers of M^2/Q^2 have been neglected.

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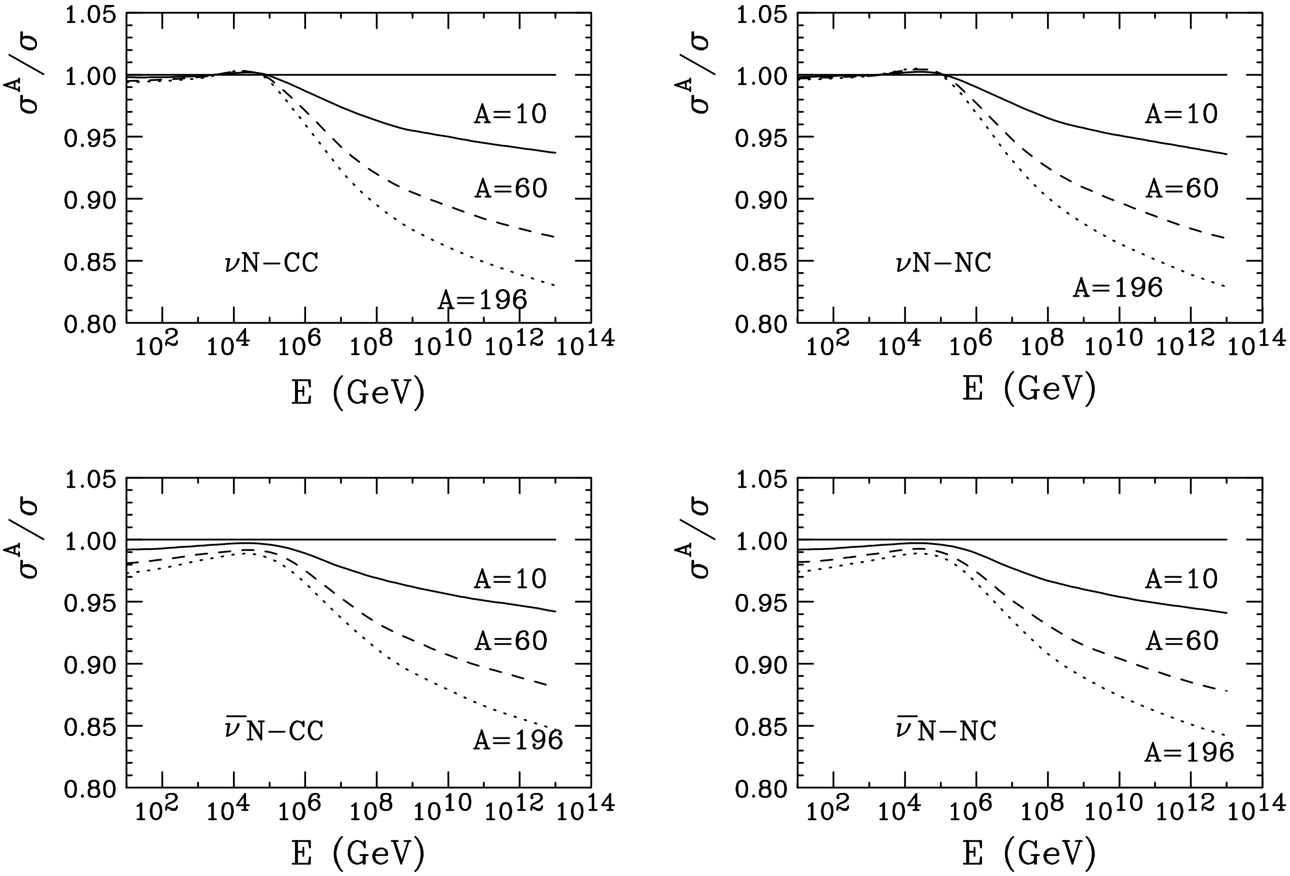

Fig. 1. The ratio of nuclear effects correted over non corrected neutrino-nucleon cross section as a function of the neutrino energy in the lab frame.

It is experimentally well known that structure functions F_2 and F_3 in deep inelastic lepton-nucleon scattering for a nucleus of large atomic mass, A, are different from those measured for hydrogen or deuterium targets (see for example Arneodo (1994) and Kulagin (1998)). If one maintains the partonic view of the nucleon, these results can be explained as if the parton distributions of bound nucleons were different from those into free nucleons.

Parton distributions of the nucleon in a nucleus containing A nucleons have been obtained in Eskola, Kolhinen and Salgado (1999) using QCD evolution at leading twist and leading order of perturbation theory together with the experimental ratios F_2^A/F_2^D measured by EMC and NMC at CERN (Arneodo, 1994; Arneodo et al, 1996). With the quark ratios defined in Eskola, Kolhinen and Salgado (1999) we have generated the corrected by nuclear effects parton distribution functions using the uncorrected MRST98 set from Martin et al (1998).

With the parton densities in bounded nucleons we have computed the total cross section (see details in Castro Pena, Parente and Zas (2001)). The comparison with the results using parton densities in free nucleons is presented in Fig. 1 where one observes that the difference between both predictions (with and without nuclear corrections) increases with energy and with the number of nucleons A at the highest energies.

For example, for $E_\nu = 10^{10}$ GeV, CC interaction and $A = 60$, the modified parton distribution functions result in a 10 % reduction of the total cross section. The correction is mainly due to the shadowing phenomena at low x. It is of the order of few per cent for the parameter range of interest in neutrino telescopes (A=10 and E=10^6 GeV) and it reaches 20 $\%$ at the highest energies (E=10^{12} GeV) and for the largest nuclear size (A=190) considered.

At this stage, it is worth to notice that new investigations based on unitarity limits make also questionable the use of current parton distribution functions for energies above 10^8 GeV (Dicus et al, 2001) because the predictions saturates the unitarity bound.

3 The quark content of the nucleon from UHE neutrino detectors

We have explored the sensitivity of neutrino-nucleon cross section related quantities to the low x behavior of quark distribution functions. In particular we focus on the so call mean inelasticity $\langle y \rangle$,

$$\langle y \rangle = \frac{1}{\sigma} \int_0^1 dy\, y\, \frac{d\sigma}{dy} \tag{2}$$

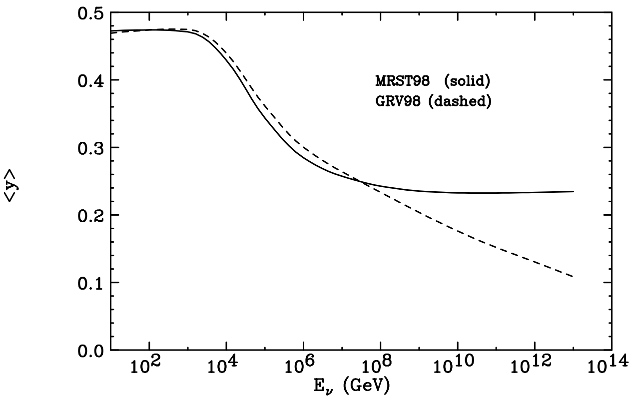

Fig. 2. The average inelasticity y in deep inelastic charged current neutrino-nucleon interaction as a function of neutrino energy.

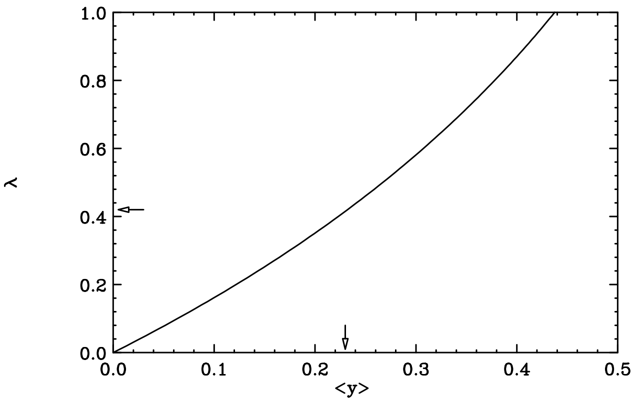

Fig. 3. The F_2 slope at low x as a function of the average inelasticity for CC neutrino-nucleon deep inelastic interaction.

being y the fraction of the neutrino energy (in the lab frame) transferred to the nucleon in the collision, which turns out to be very sensitive to the small x extrapolation of the structure function F_2.

Fig. 2 shows the significant difference in the predictions for $\langle y \rangle$ at high energy computed from two different sets of parton distribution functions: MRST98 (Martin et al, 1998) and GRV98 (Gluck, Reya and Vogt, 1998). The MRST98 set was extrapolated below the limit of aplicability, $x = 10^{-5}$, with the constant x slope that it has at $x = 10^{-5}$. The GRV98 partons can be used up to $x = 10^{-9}$ without further extrapolation.

We now extract explicitely the relation between $\langle y \rangle$ and the low x behavior of structure function F_2. Let us assume that F_2 at low x and high Q^2 is given by the power-like expression $F_2 = A(Q^2)\ x^{-\lambda}$, where λ is assumed constant (as predicted by DGLAP) or smoothly dependent on Q^2 (as predicted by BFKL in Brodsky et al (1999)). Then the CC neutrino-nucleon differential cross section (in y and Q^2) takes the form:

$$\frac{d^2\sigma}{dydQ^2} = \frac{G_F^2\ M_W^4\ A(Q^2)}{4\pi\ (M_W^2+Q^2)^2} \left(\frac{2ME_\nu}{Q^2}\right)^\lambda \frac{[1+(1-y)^2]}{y}\ y^\lambda \tag{3}$$

where in Eq. (3) we have not considered the contribution from F_L and xF_3 structure functions, expected to be negligible at low x and high Q^2.

In the calculation of the mean inelasticity $\langle y \rangle$ one has:

$$\langle y \rangle = \frac{\int_0^1 dy\ y\ \frac{d\sigma}{dy}}{\int_0^1 dy\ \frac{d\sigma}{dy}} \simeq \frac{\int_0^1 dy\ [1+(1-y)^2]\ y^\lambda}{\int_0^1 dy\ [1+(1-y)^2]\ y^{\lambda-1}} \tag{4}$$

where the Q^2 integral of Eq. (3) in the numerator and denominator of Eq. (4) cancels at high energy (provided that $2ME_\nu$ is much larger than M_W^2).

Finally, from Eq. (4) it follows the simple analytical relation:

$$\langle y \rangle \simeq \frac{\lambda^3+5\lambda^2+8\lambda}{\lambda^3+6\lambda^2+13\lambda+12} \tag{5}$$

Assuming that the mean inelasticity $\langle y \rangle$ could be experimentally determined, Eq. (5) can be inverted (see Fig. 3) to determine the F_2 slope parameter λ at small x and large Q^2 around M_W^2, Although y-measurements could be thought to be rather speculative at this early stage neutrino astronomy is at present, there is the expectation that the technique for the detection of radio pulses generated by showers produced in the neutrino-nucleon interaction could be sufficiently developed to be able to measure y, as it has been suggested in Alvarez-Muñiz, Vázquez and Zas (2000) (see the detailed discussion in Castro Pena, Parente and Zas (2001b))

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