SMALL-x PARTON DENSITIES FROM HERA AND
THE ULTRA-HIGH ENERGY NEUTRINO-NUCLEON CROSS SECTIONS

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Abstract

In light of recent measurements of the nucleon structure function in the small-x deep-inelastic regime at HERA and the consequently improved theoretical understanding of the quark distributions in this range of parton fractional momentum, we present new results for the neutrino-nucleon cross section at ultra high energies, up to $E_\nu \sim 10^{21}$ eV. The results are relevant to deep underground muon detectors looking for such neutrinos. For $\simeq 10^{20}$ eV neutrinos, our cross sections are about a factor of 4 to 10 times larger than the previously reported results by Reno, Quigg and Walker. We discuss implications of this new neutrino-nucleon cross section for a variety of current and future neutrino detectors.

1Talk presented by I. Sarcevic.
As the number of extant and planned experimental facilities for extra-terrestrial neutrino detection testifies, their importance in extending the particle physics frontier beyond the standard model is widely recognized. At the highest energies, neutrinos are decay products of pions produced in cosmic accelerators and thus provide a direct window to the most energetic processes in the universe. Neutrino astronomy also has important advantages over gamma-ray astronomy. In the energy range $10^{12}$ to $10^{20}$ eV, the expected air-cascade signature of the gamma-ray flux is dwarfed by the cosmic-ray background. In the same energy range the flux of neutrino by-products of the cosmic-ray interactions is very small, and the expected neutrino flux from cosmic accelerators should dominate. In addition, neutrino telescopes span a significant fraction of the sky at all times, in contrast to gamma-ray detectors which provide small angular coverage for a limited amount of time.

Recent observations of TeV gamma-rays from Mkn 421 and Mkn 501 have revived interest in studying mechanisms for producing high energy photons in Active Galactic Nuclei (AGN). If the observed photons are decay products of $\pi^0$s produced in hadronic interactions in the disk surrounding the AGN, then AGNs are also powerful sources of ultra high energy (UHE) neutrinos.

In general, fluxes of UHE neutrinos fall steeply with increasing energy, making the direct detection of these particles difficult. Cerenkov detectors, however, are capable of detecting upward-moving muons produced by the charged-current (CC) interactions of energetic neutrinos in the rock below the detector. The effective volume of the detector is thus enhanced in proportion to the range of the produced muon (typically several kilometers), which then may traverse the fiducial volume of the detector or stop therein. The expected event rate for these detectors is presently subject to two sources of uncertainty: a) the uncertainty in the knowledge of the incident neutrino flux, and, b) the calculation of the UHE charged current cross-section for $\nu_\mu + N \rightarrow \mu + X$, where $N$ is a nucleon. The latter stems from necessary extrapolations of the nucleon quark structure functions for very low parton fractional momentum $x$ and large momentum transfer $Q^2$.

Using recent results from the $ep$ collider at HERA on small-$x$ parton distributions, we have performed calculation of the neutrino-nucleon cross sections for neutrino energies up to $10^{21}$ eV. For $10^{20}$ eV neutrinos we have found the cross sections to be factor of four to ten times larger than previous estimates. Since UHE neutrinos are detected via neutrino-induced muons, our results translate into significantly larger probability that neutrino-induced muon created in the rock surrounding the detector would reach the detector and thus larger downward muon rates. For upward-moving muons, the neutrino attenuation in the Earth depends on the charged-current and neutral-current cross sections. For larger neutrino-nucleon cross sections, the attenuation effect is stronger. Since it is the product of the muon probability and the neutrino attenuation that goes into the calculation of the upward-moving muon event rate, one has to incorporate these two competing effects, as elaborated below.

The inclusive cross section for $\nu_\mu + N \rightarrow \mu^- + X$ is given by

$$\frac{d^2\sigma}{dx dy} = \frac{2G_F^2 M E_\nu}{\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left( x q(x, Q^2) + x (1 - y)^2 \bar{q}(x, Q^2) \right),$$

where $x = Q^2/2M \nu$, $y = \nu/E_\nu$, and $\nu$ the energy loss in the lab frame, $\nu = E_\nu - E_\mu$. The mass of the nucleon is $M$, and $M_W$ is the mass of the $W$-boson, while the Fermi constant, $G_F = 1.16 \times 10^{-5}$ GeV$^{-2}$. With the assumption that the target is an isoscalar nucleon, the quark and antiquark distribution functions, $q(x, Q^2)$ and $\bar{q}(x, Q^2)$, contain valence and sea quark contributions.

At low energies, the neutrino-nucleon cross section reduces to the usual 4-Fermi approximation and in-
creases linearly with the neutrino energy. At high energies, \( E_\nu \gg M_W^2/2M \), the \( W \)-propagator in Eq. (1) becomes important \[3\], limiting the growth of \( Q \) to \( (Q^2) \sim M_W^2 \). For \( E_\nu \sim 10^5 \) GeV, the neutrino-nucleon total cross section is dominated by the behavior of the quark densities at \( x \sim M_W^2/2ME_\nu \) and \( Q^2 \sim M_W^2 \). For neutrino energies above \( 10^5 \) GeV, the small-\( x \) (i.e., \( x \leq 3 \times 10^{-2} \)) behavior of the quark densities plays an important role in determining the cross-section.

Recently, knowledge of the parton densities at small values of \( x \) has been substantially improved by the observation of a dramatic increase of the proton structure function, \( F_2(x,Q^2) \) with decreasing \( x \) for \( 10^{-4} \leq x \leq 10^{-2} \) and 8.5 GeV2 \( \leq Q^2 \leq 15 \) GeV2 by the ZEUS and H1 Collaborations at HERA \[4\]. For larger values of \( Q^2 \), the HERA experiments have measured \( F_2^p(x,Q^2) \) down to a value of \( x = 2 \times 10^{-2} \). Thus, for neutrino energies above \( E_\nu \sim 10^5 \) GeV, the relevant small-\( x \) regime is unconstrained by experiments.

In the absence of measurements in the appropriate range of \( (x,Q) \), the parton distributions are traditionally obtained by assuming certain form at some fixed value of \( Q = Q_0 \approx \) few GeV and the distributions are evolved to larger values of \( Q \) via QCD evolution equations. The parameters in the initial parametrizations are determined by fitting a variety of experimental data on structure functions for \( x > 10^{-3} \) and moderate values of \( Q \), as well as the recent HERA data \[4\].

The theoretical uncertainties in the total cross section for UHE neutrinos in the standard model are therefore due to the parameterization at \( Q_0 \), the extrapolation to values of \( x \) below current data and in the evolution of the parton distribution functions to \( Q > Q_0 \).

Currently there are two theoretical approaches to understanding small-\( x \) evolution with \( Q \), both based on perturbative QCD. The first, and more traditional approach is to determine parton densities for \( Q > Q_0 \) by solving the next-to-leading order Gribov-Lipatov-Altarelli-Parisi (GLAP) evolution equations numerically \[3\]. Crucial to the calculation of the UHE \( \nu N \) cross section is the small-\( x \) parameterization, which in all cases has the form for sea quark distributions of \( x\bar{q}(x,Q_0^2) \sim x^{-\lambda} \). The second approach to small-\( x \) evolution is to solve the Balitskii-Fadin-Kuraev-Lipatov (BFKL) equation \[8\]. The solution predicts \( \lambda \approx 0.5 \) and a more rapid evolution with \( Q^2 \) than the GLAP evolution.

The parton distribution sets obtained perturbatively using next-to-leading order (NLO) GLAP evolution equations are applicable for the calculation of the total neutrino cross section for \( E_\nu < 10^5 \) GeV, and are a reasonable starting point for calculations for higher energy neutrinos. The NLO CTEQ3 distributions \[9\] in the deep-inelastic scattering factorization scheme (CTEQ-DIS) have \( Q_0 = 1.6 \) GeV and \( \lambda = 0.332 \). These distributions are particularly useful because the numerical evolution is provided for \( x \to 0 \), albeit, in a region where GLAP evolution is unreliable.

To estimate the uncertainty in the cross section, we consider two other distribution functions extrapolated to small-\( x \). An approximate lower limit is given by the leading order CTEQ3 distribution with the double-logarithmic-approximation (DLA) extrapolation below \( x_{\text{min}} = 10^{-4} \), labeled CTEQ-DLA below. This is an approximate solution to the leading order GLAP equations, suitable for \( \lambda \sim 0 \). We use a more singular distribution than the CTEQ-DIS distributions to indicate the upper range of the cross section. Motivated by BFKL dynamics, the MRS D_{\text{set}} \[10\] is parameterized with \( \lambda = 0.5 \). The power \( \lambda = 0.5 \) does not change significantly with \( x \) and \( Q \) for small-\( x \) and \( Q \sim M_W \), so we use a power law extrapolation below the limit of the numerically evolved distributions, namely for \( x < x_{\text{min}} = 10^{-5} \).

In Fig. 1 we present our results for the charged-current cross sections for the three choices of parton distribution functions, and compare with the calculation of Ref. \[11\] which used the Eichten et al. \[11\] distributions extrapolated using the DLA (EHLQ-DLA). We find our results to be in very good agreement.
The differences in the cross section appear at neutrino energies $E_\nu \sim 10^6$ GeV, reflecting the different behaviors of $xq_s(x,Q)$ below $x \sim M_W^2/(2M \cdot 10^6$ GeV)$\sim 3 \cdot 10^{-3}$. The $D_\perp$ and CTEQ-DIS cross sections are essentially equal for $E_\nu = 10^6$ GeV, but the CTEQ-DLA cross section is $\sim 15\%$ lower. By $E_\nu = 10^{10}$ GeV, there is a factor of 2.6 difference between the CTEQ-DLA extrapolation and the $D_\perp$ calculations of the cross section. The CTEQ-DIS result lies a factor of 1.4 above the CTEQ-DLA cross section. At $E_\nu = 10^{12}$ GeV, the discrepancy between the CTEQ-DLA and $D_\perp$ calculations is a factor of 6. One should keep in mind, however, that the DLA is an approximation valid for $E_\nu \ll 10^{11}$ GeV.

In order to calculate the number of upward-moving muons that can be detected with future neutrino detectors, such as DUMAND II, AMANDA, BAikal and NESTOR [1], we fold in the muon flux and its attenuation due to its passage through the Earth with the probability that a neutrino passing on a detector trajectory creates a muon in the rock which traverses the detector. The cross section appears in the exponent for the attenuation, and the probability is proportional to the cross section. The details are found in Ref. [5]. We find that above $10^5$ GeV, both the muon probability and the neutrino attenuation are very sensitive to the small-$x$ behavior of the sea quark distributions, but their product is not. Thus, for the downward-moving muons (and for the contained events) the event rates obtained with MRS $D_\perp$ or CTEQ distributions are much larger than the same with EHLQ structure functions, but the upward rates differ only by 17% for the whole energy range.

We find that future detectors, such as DUMAND II, AMANDA, BAikal and NESTOR have a very good chance of being able to test different models for neutrino production in the AGNs [3]. For $E_\mu > 1$ TeV, we find that 900 upward-moving muons/yr/km$^2$/sr originating from the diffuse AGN neutrinos, with the atmospheric background of 1400 events/yr/km$^2$/sr. For $E_\mu > 10$ TeV, signal to background ratio becomes even better, the signal of 500 muon events/yr/km$^2$/sr, being almost 20 times the background rate.

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