QCD dynamic effects in the neutrino absorption by the Earth's interior at IceCube neutrino energies and above*

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Abstract

We investigate how the uncertainties in $\sigma^{\nu N}$ due the different QCD dynamic models would modify the neutrino absorption while they travel across the Earth. We compare the predictions of models based on the solution of the linear DGLAP equations at small-x and large-Q^2 with those which impose the Froissart bound at large energies, taking into account the unitarity effects in the neutrino - nucleon cross section. Our results indicate that the probability of absorption and the angular distribution of neutrino events are sensitive to the QCD dynamics at ultra high energies.

INTRODUCTION

The observation of ultra high energy (UHE) neutrino events at PeV by the IceCube Collaboration marks the birth of neutrino astronomy [1, 2]. However to interpret the experimental results is fundamental to take into account that the attenuation of the neutrino beam in route to a detector is strongly dependent on the high energy behaviour of the neutrino - nucleon cross section ($\sigma^{\nu N}$), which determines the opacity of the Earth to incident neutrinos. As discussed by several authors in the last years, [3–10], at ultra high energies, the neutrino-nucleon cross section provides a probe of Quantum Chromodynamics (QCD) in the kinematic region of very small values of Bjorken-x and large virtualities Q^2, which was not explored by the HERA measurements of the structure functions [11]. The results from Ref. [7] shown that the solution of the linear Dokshitzer - Gribov - Lipatov - Altarelli - Parisi (DGLAP) equation [12] at small - x and large Q^2 obtained in Ref. [13], denoted FJKPP hereafter, provides an upper bound for the behaviour of $\sigma^{\nu N}$ at ultra high energies. In contrast, the solution proposed in Ref. [14], denoted BBMT hereafter, which imposes that $\sigma^{\nu N}$ satisfies the Froissart bound at high energies, can be considered a lower bound. As demonstrated in Ref. [7], models which taken into account of the non - linear effects to the QCD dynamics predict high energy behaviours between these extreme scenarios. In this contribution we review the results obtained in Ref. [10] where we have extended these previous studies for the analysis of the probability of neutrino absorption by the Earths interior at ultra high energies and determined the theoretical uncertainty present in this quantity. For completeness we also present the predictions obtained the CT10 parametrization [15] for the parton distributions (PDFs), derived using the DGLAP evolution equations, which allows us to estimate the uncertainty present in the global fits as well as those associated to the extrapolation of the PDFs in a kinematical range beyond that probed by HERA.

FORMALISM AND RESULTS

Neutrino DIS is described in terms of charged current (CC) interaction, which proceed through $W^{\pm}$ exchange, and is written as

$$\sigma_{\nu h}^{CC}(E_\nu) = \int_{Q^2_{min}}^{s} dQ^2 \int_{Q^2/s}^{1} dx \frac{1}{xs} \frac{\partial^2 \sigma^{CC}}{\partial x \partial y} \ , \tag{1}$$

where E_ν is the neutrino energy, $s = 2ME_\nu$ with M the hadron mass, $y = Q^2/(xs)$. Also, the differential cross section is given by

$$\frac{\partial^2 \sigma_{\nu h}}{\partial x \partial y} = \frac{G_F^2 M E_\nu}{\pi} \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[\frac{1 + (1-y)^2}{2} F_2^h(x, Q^2) \frac{y^2}{2} F_L^h(x, Q^2) + y(1 - \frac{y}{2}) x F_3^h(x, Q^2) \right] \tag{2}$$

where $h = p$ or A, with A the atomic number, G_F is the Fermi constant and M_W denotes the mass of the charged gauge boson. In the QCD improved parton model the structure functions F_2, F_L and F_3 are calculated in terms of quark and gluon distribution functions. For completeness we include in our calculations the anti electron neutrino resonant scattering with electrons in the medium [16].

In Fig. 1 (a) we compare the antineutrino cross-section as given by antineutrino-electron resonant scattering with the CC neutrino-nucleon cross-section. We see that the former is only important in the region around the resonance, defined by $(M_W - 2\Gamma_W)/2m_e^2 \approx 5.7$ PeV $\leq E_\nu \leq (M_W + 2\Gamma_W)/2m_e^2 \approx 7$ PeV. The shaded band is due to the propagation of the uncertainty present in the data fits as well as those associated to the extrapolation of the PDFs in a kinematical range beyond that probed by HERA. We obtain that both models based on linear dynamics, GQRS [4], FJKPP and CT10, predicts a strong growth of CC neutrino-nucleon cross-section when compared with the Froissart based model BBMT, being the difference of a factor of two at $E_\nu = 10^{11}$ GeV and increases to ≈ 5 at $E_\nu = 10^{13}$ GeV.

Following [4] we define the the probability of neutrino interact while crosses the Earth as

$$P^j_{Shad}(E_\nu) = exp\left\{ -N_A \ \sigma_{\nu_j}(E_\nu) \int_0^{r_f(\theta)} \rho_i(r) dr \right\} \ , \tag{3}$$

where j represents each final state of resonant scattering, or the CC neutrino-nucleon interaction. In this work we use the density profile from [17]. At this point we integrate

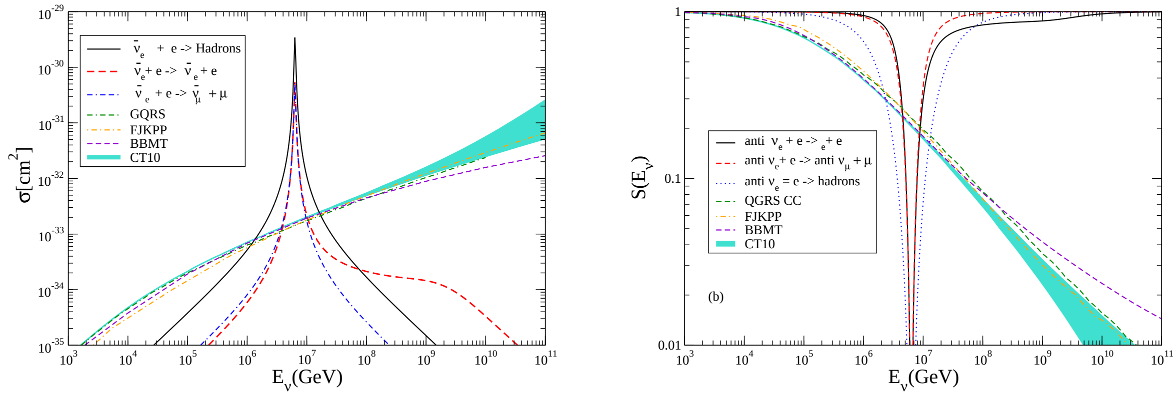

FIG. 1: (a): Comparison between CC neutrino-nucleon cross-section for the hadronic models we discuss and the antineutrino-electron resonant cross-section for the different final states relevant in this analysis. (b): Comparison of function $S(E_\nu)$ as given by Eq. (4) for the different νN interaction models we probe as well $\bar{\nu}_e e^-$ resonant scattering.

Eq. (3) with respect to the zenith angle, and define the absorption function for the neutrinos while it crosses the Earth as

$$S^i(E_\nu) = \int_{-1}^{0} dcos(\theta_\nu) P^i_{shad}(E_\nu) = \int_{-1}^{0} dcos(\theta_\nu) \;\; exp\left\{ -N_A \; \sigma_{\nu_i}(E_\nu) \int_0^{r(\theta)} \rho_i(r) dr \right\} \;, \quad (4)$$

where $i = e, N$. The integration over zenith angle tends to smear the absorption effects, as we can see if Fig. 1 (b), where the width of Glashow resonance absorption is reduced significantly. On the other hand we have that the difference between the FJKPP (CT10) and BBMT predictions increases for higher neutrino energy and becomes a factor 2 at $E_\nu \approx 10^{10}$ GeV, with the BBMT one being an upper bound. This difference of a factor 2 between the predictions has a strong impact in the analysis and interpretation of the possible few events that should be observed at such UHE.

As a summary of our main conclusions, in this contribution we have estimated the impact of the current uncertainty in the description of νN interactions at ultra high energies in the absorption of neutrinos crossing the Earth until the detectors. Our results indicated that the the probability of absorption is sensitive to the treatment of the QCD dynamics at ultra high energies. We also verified that, as this probability is proportional to the distance travelled by neutrinos and the net quantity of nuclear matter they crosses, the angular distribution of neutrino events should be modified when we impose a Froissart-like behaviour at neutrino-nucleon cross-section. Such results have direct implication in the determination of sources of UHE neutrinos below the horizon of IceCube neutrino observatory and in the analysis of the neutrino events in future experiments.

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