Investigating the physics of ultrahigh energy neutrinos in neutrino telescope experiments

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Abstract

We compute the corresponding number of events for PeV energy neutrinos for typical neutrino telescopes as the IceCube experiment. We consider different parametrizations for the νN cross section, including predictions from the geometric scaling phenomenon. The theoretical uncertainty for the number of events is investigated.

Introduction

One important property of the nonlinear perturbative QCD approaches for high energy deep inelastic $ep(A)$ scattering is the prediction of the geometric scaling (GS) [2]. Namely, the total $\gamma^*p(A)$ cross section at large energies is not a function of the two independent variables x and Q^2, but is rather a function of the single variable $\tau_A = Q^2/Q^2_{\mathrm{sat,A}}$. As usual, Q^2 is the photon virtuality and x the Bjorken variable. The saturation momentum $Q^2_{\mathrm{sat,A}}(x;\,A) \propto \frac{xG_A(x,Q^2_{\mathrm{sat}})}{\pi R_A^2} \simeq A^{\alpha}\,x^{-\lambda}$ ($\alpha \simeq 1/3$, $\lambda \simeq 0.3$) is connected with the phenomenon of gluon saturation. It is expected that the rise of the gluon distribution function at small values of Bjorken x be naturally tamed by saturation and circumvent the subsequent violation of unitarity. Some years ago, the high energy lepton-hadron, proton-nucleus and nucleus-nucleus collisions have been related through GS (see Ref. [2]). Within the color dipole picture and making use of a rescaling of the impact parameter of the γ^*h cross section in terms of hadronic target radius R_h, the nuclear dependence of the γ^*A cross section is absorbed in the A-dependence of the saturation scale via GS. The relation reads as [2]:

$$\sigma_{tot}^{\gamma^*A}(\tau_A) = \frac{\pi R_A^2\,\sigma_{tot}^{\gamma^*p}(\tau_p=\tau_A)}{\pi R_p^2},\,,\ \text{with}\ \tau_A = \tau_p\left(\frac{\pi R_A^2}{A\pi R_p^2}\right)^{\Delta},\ \text{and}\ \ \tau_p = \frac{Q^2}{Q^2_{\mathrm{sat}}(x)}, \tag{1}$$

where the nuclear saturation scale was assumed to rise with the quotient of the transverse parton densities to the power $\Delta = 1/\delta$. The nucleon saturation momentum is set to be $Q^2_{\mathrm{sat}}(x) = (x_0/\bar{x})^{\lambda}$ GeV^2, where $x_0 = 3.04\cdot 10^{-4}$, $\lambda = 0.288$ and $\bar{x} = x\,[1+(4m_f^2/Q^2)]$, with $m_f = 0.14$ GeV. The nuclear radius is given by $R_A = (1.12A^{1/3} - 0.86A^{-1/3})$ fm. The following functional shape for the photoabsortion cross section has been considered based on theoretical motivations [2]:

$$\sigma_{tot}^{\gamma^*p}(\tau_p) = \bar{\sigma}_0\,[\gamma_E + \Gamma(0,\beta) + \ln(\beta)]\,,\quad \text{where}\ \ \beta = a/\tau_p^{\,b}\,, \tag{2}$$

where γ_E is the Euler constant and $\Gamma(0,\beta)$ the incomplete Gamma function. The parameters for the proton case were obtained from a fit to the small-x ep DESY-HERA data, producing $a = 1.868$, $b = 0.746$ and the overall normalization was fixed by $\bar{\sigma}_0 = 40.56$ μb. The parameters for the nuclear saturation scale were determined by fitting the available lepton-hadron data using the relation in Eq. (1) and the same scaling function, Eq. (2). One obtains $\delta = 0.79 \pm 0.02$ and $\pi R_p^2 = 1.55 \pm 0.02$ fm^2.

The theoretical achievements summarized above have direct consequences on the computation of the cross sections of interaction of neutrinos with nucleons and atomic nuclei. **Ultrahigh energy (UHE) neutrino reactions are sensitive upon the behavior of the nucleon/nuclear structure functions at extremely low-x values and relatively large scales of electroweak boson virtualities**. Namely, they can probe the domain $x \simeq m^2_{W,Z}/E_\nu \sim 10^{-8}$ at $E_\nu \sim 10^{12}$ GeV and virtualities $Q^2 \sim m^2_{W,Z} \approx 10^4$ GeV^2, where $m_{W,Z}$ are the boson masses. Therefore, accurate predictions for UHE neutrinos require precise extrapolation of the structure functions to the small-x. A very important feature is that, within the color dipole framework [3, 4], the charged (CC) and neutral (NC) current structure functions are described by the same mathematical expressions as the proton structure function up to a different coupling of the electroweak bosons. Therefore, the GS property should be present also in neutrino scattering on hadron targets and allows to obtain the dependences on energy and atomic number of CC/NC cross sections, which are encoded in the nuclear saturation momentum.

In 2012, the IceCube Collaboration announced an observation of two ~ 1 PeV neutrinos discovered in a search for the nearly guaranteed cosmogenic neutrinos. The search technique was later refined to extend the neutrino sensitivity to lower energies, resulting in the discovery of an additional event candidates. The last six-year data set [5] contains a total of 82 neutrino event with deposited energies ranging from 60 TeV to 10 PeV, which are consistent with an astrophysical component with a spectrum close to E_ν^{-2} above an energy of ~ 200 TeV. This year [1], a multiteam collaboration detected a high-energy neutrino event whose arrival direction was consistent with a known blazara type of quasar with a relativistic jet oriented directly along our line of sight. The blazar, TXS 0506+056, was found to be undergoing a gamma-ray flare, prompting an extensive multiwavelength campaign. Thus, blazars are probable sources of astrophysical neutrinos.

Theoretical approach

Deep inelastic neutrino scattering can proceed via $W^\pm$ (CC) or Z^0 (NC) exchanges. The standard kinematical variables describing them are given by $s = 2\,m_N E_\nu$ (center-of-mass energy squared), Q^2 (boson virtuality), Bjorken x and $y = Q^2/xs$ (inelasticity variable). Here, m_N is the nucleon mass and E_ν labels the neutrino energy. At small-x, a successful framework describing QCD interactions is provided by the color dipole formalism [3, 4], which allows an all-twist computation of the structure functions. The physical picture of the interaction is the deep inelastic scattering (DIS) at low x viewed as the result of the interaction of a color $q\bar{q}$ dipoles, which are fluctuations of the electroweak gauge bosons, with the hadron target. The interaction is modeled via the dipole-target cross section, whereas the boson fluctuation in a color dipole is given by the corresponding wave function. The DIS structure functions for neutrino scattering read as [3, 4],

$$F_{T,L}^{\mathrm{CC,NC}}(x,Q^2) = \frac{Q^2}{4\,\pi^2}\,\sigma_{tot}\,(W^\pm(Z^0)\,N \to X)\,, \tag{3}$$

$$\sigma_{tot}\,(W^\pm(Z^0)\,N) = \int d^2\boldsymbol{r}\int_0^1 dz\,|\psi^{W^\pm,Z^0}(z,Q^2,r)\,|^2\,\sigma_{dip}(x,r;A)\,, \tag{4}$$

where $\boldsymbol{r}$ denotes the transverse size of the color dipole, z the longitudinal momentum fraction carried by a quark and $\psi_{T,L}^{W,Z}$ are the sum over dipoles of the wave functions of the charged or neutral gauge bosons, respectively. Their explicit expressions can be found for instance in Refs. []. Here one considers only four flavors (u,d,s,c) assumed to be massless. Heavy quarks (b,t) give relatively small contribution and will be disregarded. Color dipoles contributing to Cabibbo favored transitions are $u\bar{d}\,(d\bar{u})$, $c\bar{s}\,(s\bar{c})$ for CC interactions and $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ for NC interactions. The dipole cross section $\sigma_{dip}\,(x,\boldsymbol{r};A)$, describing the dipole-target interaction, is substantially affected by saturation effects at dipole sizes $\boldsymbol{r} \gtrsim 1/Q_{\mathrm{sat}}$. Based on the fact that the expressions for the photon wavefunction and the electroweak gauge bosons, appearing on Eq. (4), are exactly the same up to the different coupling of the bosons to the quark color dipole, we can simply write,

$$\sigma_{tot}^{(W^\pm N)}(x,\,Q^2;\,A) = \frac{4\,\sigma_{tot}^{(\gamma^*N)}(x,\,Q^2;\,A)}{\alpha_{\mathrm{em}}\sum_f e_f^2},\quad \sigma_{tot}^{(Z^0N)}(x,\,Q^2;\,A) = \frac{K_{\mathrm{chiral}}\sigma_{tot}^{(\gamma^*N)}(x,\,Q^2;\,A)}{\alpha_{\mathrm{em}}\sum_f e_f^2}\,, \tag{5}$$

where α_{em} is the QED constant coupling, e_f is the electric charge of the quark of flavor f. The constant $K_{\mathrm{quiral}} = (L_u^2 + L_d^2 + R_u^2 + R_d^2)$ is the sum of the chiral couplings expressed as functions of the Weinberg angle θ_W. We will use the expressions above to calculate the UHE neutrino cross section.

Main Results and Conclusions

UHE neutrinos are detected by observing the Cherenkov radiation from secondary particles produced by neutrinos interacting inside large volumes of highly transparent ice or water. Assume, for simplicity, that the neutrino direction is perpendicular to a side of the cube. To a first approximation, a neutrino incident on a side of area L^2 will be detected provided it interacts within the detector volume, i.e. within the instrumented distance L. That probability is $P = 1 - \exp(-L/\lambda_\nu) \simeq L/\lambda_\nu$, with $\lambda_\nu = (\rho N_A \sigma_\nu)^{-1}$. Here ρ is the density of the ice or water, N_A Avogadro's number and σ_ν the neutrino-nucleon cross section. A source neutrino flux $\mathcal{F}$ (neutrinos per cm^2 per second) crossing a detector with cross sectional area A ($\simeq L^2$) facing the incident beam, will produce $\mathcal{N} = ATP\mathcal{F}$ events after a time T. In practice, the quantities A, P and $\mathcal{F}$ depend on the neutrino energy and $\mathcal{N}$ is obtained by a convolution over neutrino energy above the detector threshold. The total number of target nucleons present in one km^3 of ice is: $N_T = \rho_{\mathrm{ice}}\,N_A\,V \sim 6\times 10^{38}$, where $\rho_{\mathrm{ice}} \sim 1\ \mathrm{g/cm^3}$ is the density of ice, $N_A = 6.02\times 10^{23}$ mol^{-1} is Avogadro's number, and $V = 10^{15}\ \mathrm{cm}^3$ is the total volume. Assuming the Earth is completely opaque to the propagtion of neutrinos (i.e., an effective aperture for detection at IceCube of 2π sr) the total number of events expected in $T = 6$ yr in a given energy beam $\bar{E}_\nu$, is:

$$\mathcal{N} = 2\pi\,N_T\,T\int_{\bar{E}_\nu-\Delta}^{\bar{E}_\nu+\Delta}\mathcal{F}(E_\nu)\,\sigma(E_\nu)\,dE_\nu. \tag{6}$$

In Fig. (1) we present the six-year IceCube data for PeV neutrinos, including the curve for background atmospheric neutrinos (solid green line). The prediction using QCD color dipole approach (using geometric scaling phenomenon) is represented by solid red line for $E_\nu > 100$ TeV. For comparison, the full NLO DGLAP calculation (without gluon saturation) is also presented (dashed line). Both are in agreement to data, where color dipole prediction has a less step behavior compared to usual QCD calculations. The advantage here is the analytical expression for $\sigma(E_\nu)$ in the QCD dipole approach and the limitation in present calculation is the oversimplified assumption for the source flux (we also assume the same flux for all neutrino flavour and the Waxman-Bahcall bound $\mathcal{F}_\nu(E_\nu) \simeq\ 6.0\times 10^{-8}(E_\nu/\mathrm{GeV})^{-2}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$) and effective area. Future plans will be include realist inputs for source flux and effective area and information on the neutrino arrival directions.

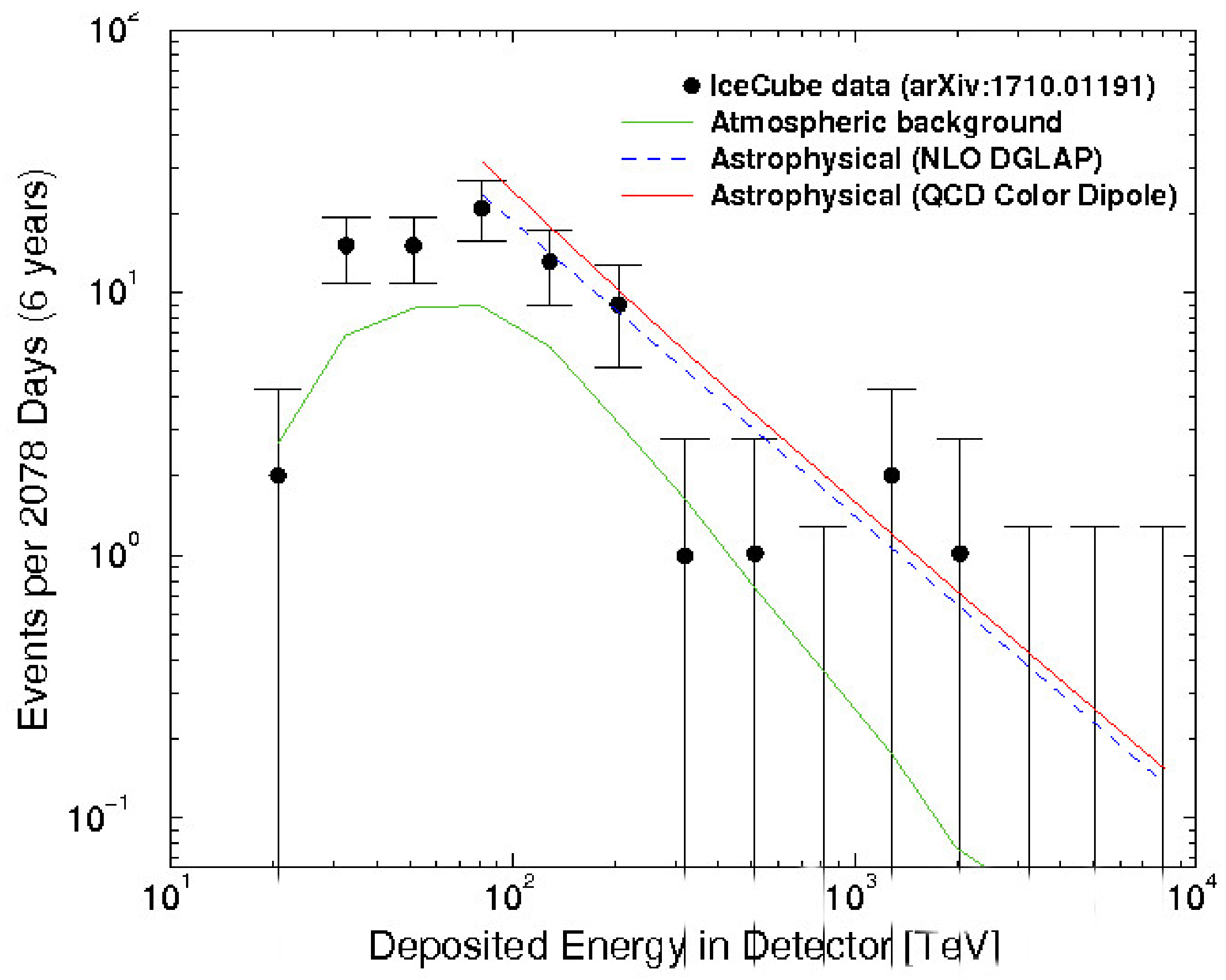

Figure 1: Theoretical predictions for number of events, $\mathcal{N}$, for astrophysical UHE neutrinos compared to IceCube data as a function of neutrino energy, $\bar{E}_\nu$, in units of TeV. Atmospheric neutrino background is also shown.

References

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