Probing low-x QCD with cosmic neutrinos at the Pierre Auger Observatory

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The sources of the observed ultra-high energy cosmic rays must also generate ultra-high energy neutrinos. Deep inelastic scattering of these neutrinos with nucleons on Earth probe center-of-mass energies $\sqrt{s} \sim 100$ TeV, well beyond those attainable at terrestrial colliders. By comparing the rates for two classes of observable events, any departure from the benchmark (unscreened perturbative QCD) neutrino-nucleon cross-section can be constrained. Using the projected sensitivity of the Pierre Auger Observatory to quasi-horizontal showers and Earth-skimming tau neutrinos, we show that a 'Super-Auger' detector can thus provide an unique probe of strong interaction dynamics.

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A new window on the Universe is expected to open soon through the observation of ultra-high energy cosmic neutrinos by detectors such as the Pierre Auger Observatory [1] and IceCube [2]. The study of their interactions in the Earth's atmosphere and crust is particularly interesting as this provides a probe of QCD in the kinematic region of very small values of Bjorken-x: $x < 10^{-3}$, where conventional calculations done in the DGLAP framework become inadequate.

The surprising discovery at HERA that the gluon distribution function rises sharply with decreasing x for high virtuality of the exchanged gauge boson Q^2, implies a strong increase in the neutrino-nucleon total cross-section. This would however violate unitarity (the Froissart bound) if continued indefinitely, hence there *must* be a departure from this behavior at very low values of x.

Various possibilities have been entertained in this context (see e.g., [3] for a recent review) which predict a slower rise of the cross-section than the usual DGLAP evolution based calculation [4] commonly adopted for estimating the effective aperture of detectors, e.g. of Auger, which is sensitive to neutrinos of energy $\gtrsim 10^8$ GeV [5]. Thus, a measurement of the neutrino-nucleon cross-section at such energies, even if relatively crude, would nonetheless be of great interest. For example one can directly test models where saturation effects cause the gluon distribution function to freeze or even *decrease* with x below some threshold, $x \lesssim 10^{-5}$. The former implies a $\nu - N$ cross-section which stays about a factor of 2 below the standard expectation for $E_\nu \sim 10^8 - 10^{10}$ GeV, where Auger is most sensitive. In the latter case the cross-section remains sensibly constant with increasing energy above $\sim 10^9$ GeV, so has a value 10 times below the usual expectation at the upper end of this range.

One might wonder how such a measurement can be done given the large uncertainties in the expected fluxes of (the yet to be detected!) cosmic neutrinos. The opportunity arises because of the discovery that the muon and tau neutrinos are maximally mixed. Hence cosmic neutrino beams, generally expected to be ν_μ's and ν_e's from the decays of pions, kaons and perhaps heavy flavours, will necessarily contain a substantial component of ν_τ's by the time they reach Earth [6]. It has been noted [7, 8, 9] that Earth-skimming ν_τ's will generate *upward* going air showers when they interact in the crust. By contrast neutrinos of all flavours will generate deeply penetrating quasi-horizontal air showers which are distinctive in having an electromagnetic component unlike hadron-initiated air showers at such large inclinations [10]. The crucial observation [11] is that while the rate of quasi-horizontal ν-showers is proportional to the $\nu - N$ cross-section, the rate of detectable Earth-skimming ν_τ's is not. This is because of several effects which come into play in the latter case. For example, a decrease in the cross-section will increase the number of τ's produced in a region close enough to Earth's surface that are likely to escape. However, the resulting τ's emerge preferentially at angles outside the acceptance typical of surface arrays. Consequently, the number of detected τ's is relatively independent of the cross-section. All in all, the *ratio* of the two classes of events provides a measure of the absolute $\nu - N$ cross-section, even when there are large uncertainties in the incoming cosmic flux.

For example although the (so far unknown) sources of the observed ultra-high energy cosmic rays *must* also be sources of ultra-high energy neutrinos, it is difficult to calculate the expected neutrino flux in terms of the observed cosmic ray flux, given our ignorance of the opacity of the sources. The usual benchmark here is the so-called (all flavours) Waxman-Bahcall flux [12]

$$\phi^{\nu}_{\rm WB} \simeq 4 \times 10^{-8} \, (E_\nu/{\rm GeV})^2 \, {\rm GeV \, cm^{-2} \, s^{-1} \, sr^{-1}}, \quad (1)$$

for $10^3 \lesssim E_\nu/{\rm GeV} \lesssim 10^{11}$, derived assuming that the sources are 'transparent' and that 60% of the proton energy is converted to pions. We will use this flux to estimate the event rates for various models of the neutrino scattering cross-section.

The cross-section for charged current (CC) $\nu - N$ scattering is [13]

$$\sigma_{\rm pQCD} = \int_0^1 {\rm d}x \int_0^{xs} {\rm d}Q^2 \frac{{\rm d}^2\sigma^{\nu N}}{{\rm d}x {\rm d}Q^2} \, , \quad (2)$$

where

$$\frac{\mathrm{d}^2\sigma^{\nu N}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{G_\mathrm{F}^2}{2\pi x}\left(\frac{m_W^2}{Q^2+m_W^2}\right)^2\Big[Y_+\,F_2(x,Q^2) - y\,F_\mathrm{L}(x,Q^2) + Y_-\,xF_3(x,Q^2)\Big] \quad (3)$$

is the differential cross-section given in terms of the structure functions F_2, F_L and xF_3, and $Y_+ = 1+(1-y)^2$, $Y_- = 1-(1-y)^2$ with $y = Q^2/sx$ ($s = 2E_\nu m_N$ is the center-of-mass (c.m.) energy, G_F is the Fermi constant and m_W is the W-boson mass). For simplicity, we are considering only CC interactions, as neutral current (NC) interactions are subdominant. At leading order (LO) in perturbative QCD, the structure functions are given in terms of parton distributions as $F_2 = \sum_i x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$, $xF_3 = \sum_i x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$ and $F_\mathrm{L} = 0$. However at NLO these relationships involve further QCD-calculable coefficient functions and contributions from F_L can no longer be neglected. Parton distribution functions (PDFs) are determined in fits to deep inelastic scattering (DIS) data by the following procedure. The parton distribution functions are parameterised at some initial scale $Q_0 \sim 1$ GeV and then evolved, using the next-to-leading order (NLO) DGLAP equations, to higher values of Q^2; they are then convoluted with QCD-calculable coefficient functions to give NLO predictions for the structure functions, which are then fitted to the DIS data [13]. Such fits have been made by several different groups [14, 15, 16]; recent analyses have included estimates of the uncertainties on the PDFs coming from experimental uncertainties.

As Q^2 increases, the parton distribution functions (particularly of the gluon) grow due to QCD evolution, so that the neutrino cross-section will also grow until the propagator cuts off the growth at $Q^2 \sim m_W^2$. Hence the typical x value probed is $x \sim m_W^2/2m_N E_\nu$ [17]. For neutrino energies $E_\nu \sim 10^8 - 10^{10}$ GeV this translates into small x values of $10^{-4} - 10^{-6}$ at $Q^2 \sim 10^4$ GeV^2. HERA measurements do extend down to $x \sim 10^{-6}$, but only at $Q^2 < 0.1$ GeV^2, while for $Q^2 \sim m_W^2$ the LHC will probe $5\times10^{-4} < x < 5\times10^{-2}$. To probe down to the same kinematic region as Auger would require a hadron collider with c.m. energy exceeding 10^3 TeV.

At small x and high Q^2 the $\nu - N$ cross-section is dominated by sea quarks produced by gluon splitting $g \to q\bar{q}$. In this kinematic region, the parametrisation of the gluon momentum distribution is approximately: $xg(x,Q_0^2) \propto x^{-\lambda}$ for $x \ll 1$, where $\lambda \simeq 0.3 - 0.4$. The resulting CC $\nu - N$ cross-section was originally calculated at leading order using 1996 parton distribution functions and parametrised as: $\sigma_\mathrm{unscr}^\mathrm{LO} = 5.53\,(E_\nu/\mathrm{GeV})^{0.363}$ pb for $10^7 \le E_\nu \le 10^{12}$ GeV [4]. This is the benchmark *unscreened* cross-section widely used to evaluate sensitivities of ultra-high energy cosmic neutrino detectors. We show this in Fig. 1 along with our updated calculation using a modern PDF analysis [16] which included the final data from the first phase of HERA running (1993–2000); this data is *essential* to obtain information on the PDFs at low-x. Our NLO analysis includes corrections for heavy flavours, and, most importantly, a full treatment of experimental uncertainties which were not considered in [4]. We also show in Fig. 1 a simple power-law fit to our improved CC $\nu - N$ cross-section:

$$\sigma_\mathrm{unscr}^\mathrm{NLO} = 6.04 \pm 0.40\,(E_\nu/\mathrm{GeV})^{0.358\pm0.005}\ \mathrm{pb}\ , \quad (4)$$

for $10^7 \le E_\nu \le 10^{12}$ GeV. (The tabulated cross-section and other details are provided elsewhere [18].)

However, when x is small two further considerations are relevant. First, when x is sufficiently small that $\alpha_\mathrm{s}\ln(1/x) \sim 1$, it is also necessary to resum these large logarithms, using the BFKL formalism. Second, the gluon density at small-x is very high and both the DGLAP and the BFKL formalisms neglect non-linear screening effects due to gluon recombination. Such effects would tame the rise of the gluon distribution function at small x and may even lead to saturation. An efficient way of modelling this is the color dipole framework in which DIS at low x is viewed as the interaction of the $q\bar{q}$ dipole to which the gauge bosons fluctuate. An unified BFKL/DGLAP calculation supplemented by screening effects, as well as nuclear shadowing (following the calculation in [19] for $A = 12$), predicts a decrease of the cross-section $\sigma_\mathrm{scr}^\mathrm{KK}$ by a factor of $\sim 1.2 - 2$ in the relevant energy range [20]. An alternative recent approach uses the colour glass condensate formalism [21]; this predicts a similar suppression when a dipole model [22] which fits data from RHIC is used [23]. The predicted cross-section $\sigma_\mathrm{scr}^\mathrm{HJ}$ is even lower if a different dipole model developed to fit the HERA data [24] is used and the gluon distribution is assumed (more speculatively) to *decrease* for $x < 10^{-5}$ [23]. As seen in Fig. 1 this is a factor of $\sim 2 - 20$ below the unscreened cross-section in the relevant energy range. Other possibilities for the high energy $\nu - N$ cross-section have been discussed [25]; an exciting development formulates DIS using gauge/string duality and provides new insights into low-x dynamics [26].

The Pierre Auger Observatory is the largest cosmic ray detector in the world [1] and when complete will occupy two sites — one in the Southern and one in the Northern hemisphere. Construction of Auger South on a plateau in Western Argentina is well advanced and it is operating in hybrid mode employing fluorescence detectors overlooking a ~ 3000 km^2 ground array of water Čerenkov detectors. In addition to studying the highest energy cosmic rays, Auger is also capable of observing ultra-high energy cosmic neutrinos [5, 8].

Given an isotropic flux of neutrinos $\phi^\nu(E_\nu)$, the rate of quasi-horizontal (QH) showers expected to be observed at Auger is proportional to the $\nu - N$ cross-section:

$$\mathcal{N}_\mathrm{QH} \propto \int \mathrm{d}E_\mathrm{sh}\ \sigma_{\nu N}(E_\nu)\ A_\mathrm{QH}(E_\mathrm{sh},\theta_\mathrm{z})\ \phi^\nu(E_\nu)\,. \quad (5)$$

Here $A_\mathrm{QH}(E_\mathrm{sh},\theta_\mathrm{z})$ is the Auger acceptance, which depends on the zenith angle θ_z [27], and $E_\mathrm{sh} = yE_\nu$ for ν_μ and ν_τ, whereas $E_\mathrm{sh} = E_\nu$ for ν_e. The expected event rate for the WB flux (Eq.1) is given in Table I.

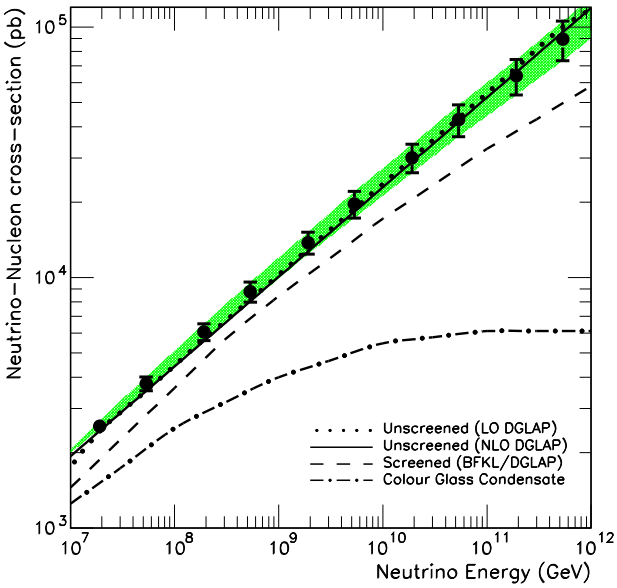

FIG. 1: Predicted cross-sections for neutrino-nucleon scattering at high energies. The line with its 1σ error band is the fit (Eq.4) to our calculated $\sigma^{\rm NLO}_{\rm uns}(E_\nu)$ (points with error bars). For comparison we show $\sigma^{\rm LO}_{\rm uns}(E_\nu)$ (dotted line) [4], $\sigma^{\rm KK}_{\rm scr}(E_\nu)$ (dashed line) [20], and $\sigma^{\rm HJ}_{\rm scr}(E_\nu)$ (dot-dashed line) [23].

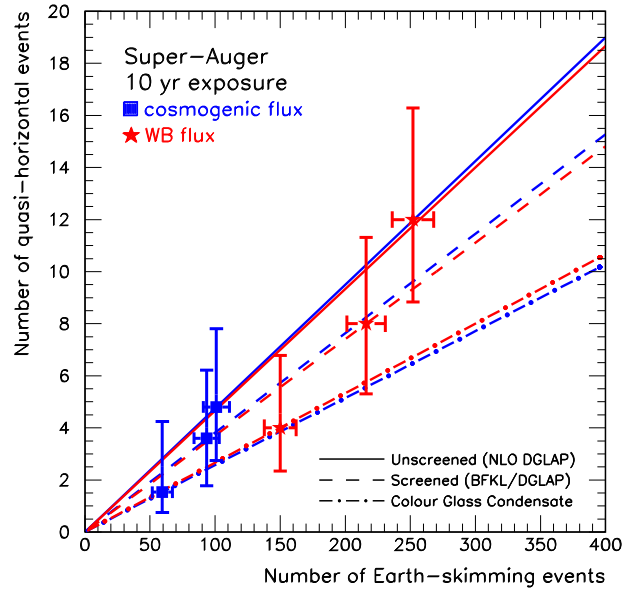

FIG. 2: The expected number of Earth-skimming and quasi-horizontal neutrino events above 10^8 GeV for different models of the $\nu - N$ cross-section; for each model, one of the lines assumes the cosmogenic spectrum and the other line the Waxman-Bahcall spectrum. We show as squares and stars respectively, the corresponding hypothetical measurements (with 1σ statistical errors) that could be made in 10 yr with an Auger-like detector scaled up to 10000 square miles.

TABLE I: Neutrino events per year at Auger for different models of the $\nu - N$ cross-section, adopting two benchmark cosmic fluxes and shower energy threshold of $10^8(10^9)$ GeV.

Model	Waxman-Bahcall		Cosmogenic	
	$\mathcal{N}_{\rm QH}$	$\mathcal{N}_{\rm ES}$	$\mathcal{N}_{\rm QH}$	$\mathcal{N}_{\rm ES}$
$\sigma^{\rm LO}_{\rm unscr}$	0.15 (0.092)	3.0 (0.62)	0.061 (0.039)	1.2 (0.35)
$\sigma^{\rm NLO}_{\rm unscr}$	0.14 (0.080)	3.0 (0.61)	0.057 (0.036)	1.2 (0.34)
$\sigma^{\rm KK}_{\rm scr}$	0.10 (0.057)	2.7 (0.54)	0.042 (0.027)	1.1 (0.31)
$\sigma^{\rm HJ}_{\rm scr}$	0.048 (0.022)	1.8 (0.32)	0.018 (0.010)	0.7 (0.18)

The situation is different for showers initiated by τ's created by CC interactions of Earth-skimming (ES) ν_τ's. To a first approximation the number of such events is

$$\mathcal{N}_{\rm ES} \propto \int {\rm d}E_{\rm sh}\ {\rm d}\cos\theta\ {\rm d}\phi\ P(\theta,\phi) A_{\rm ES}(E_{\rm sh},\theta)\phi^\nu(E_\nu)\ , \tag{6}$$

where

$$P(\theta,\phi) = \int_0^\ell \frac{{\rm d}z}{l_\nu^{\rm CC}} {\rm e}^{-z/l_\nu^{\rm tot}}\ \Theta\left[z-(\ell-l_\tau)\right] \tag{7}$$

is the probability for a ν_τ with incident nadir angle θ and azimuthal angle ϕ to emerge as a detectable τ. Here $l_\tau \sim 10$ km is the typical τ path length [9], $\ell = 2R_\oplus \cos\theta$ is the chord length of the intersection of the neutrino trajectory with the Earth (of radius $R_\oplus \approx 6371$ km), $l_\nu^{\rm CC}$ and $l_\nu^{\rm tot}$ are the CC and total neutrino mean free paths, respectively, and $A_{\rm ES}(E_{\rm sh},\theta)$ is the experimental acceptance which has a strong dependence on the angle, since the surface detector array can only see events within a few degrees of the horizon [10]. In fact, the analytic expression above is an oversimplification; it does not allow for τ regeneration in the Earth and the τ path length is not really a step-function. To take such details into account, we have carried out a simple Monte Carlo simulation assuming the NC cross-section to be 40% of the CC cross-section for all models. The resulting ES event rates are given in Table I — we find good agreement with results from a sophisticated Monte Carlo that models the environment of Auger and its acceptance accurately [28].

To evaluate the sensitivity to the assumed spectral index we also consider the "guaranteed" cosmogenic neutrino flux which has a peaked distribution in the energy range of interest [29]. As shown in Table I, if we consider events with $E_{\rm sh}^{\rm th} > 10^8$ GeV, the change in the spectrum produces a variation in the ratio $\mathcal{N}_{\rm QH}/\mathcal{N}_{\rm ES}$ of less than 5%. We have also verified that a more steeply falling flux $\propto E^{-2.54}$ (with the same $E_{\rm sh}^{\rm th}$) causes a change in $\mathcal{N}_{\rm QH}/\mathcal{N}_{\rm ES}$ by about 10% (e.g, for $\sigma^{\rm NLO}_{\rm unscr}$, $\mathcal{N}_{\rm QH} = 0.69$ yr^{-1} and $\mathcal{N}_{\rm ES} = 12$ yr^{-1}). Such a flux is expected [30] if extragalactic cosmic rays from 'transparent' sources begin dominating the observed spectrum at $10^{9.6}$ GeV [31] rather than at $\sim 10^{10.5}$ GeV as is usually assumed (see Fig. 5 in [27] for a comparison of these fluxes). Thus we conclude that the ratio $\mathcal{N}_{\rm QH}/\mathcal{N}_{\rm ES}$ provides a *robust* estimate of the $\nu - N$ cross-section [32].

Now we discuss the precision with which such a measurement can be made. In Fig. 2 we show the numbers of QH and ES events expected for different cross-section predictions and flux expectations. The data points are hypothetical measurements made over 10 years with a proposed 'Super Auger' array of area 10000 square miles (25600 km^2). Note that by observing just a dozen QH events, we can begin to distinguish between the theoretical models, however from Table I we see that the number of events for the WB flux is an order of magnitude smaller in Auger even after 10 years. Hence we are led to entertain the idea of scaling up the array by an order of magnitude, perhaps by using radio detection methods [33]. Another possibility is to use satellite-borne fluorescence detectors such as EUSO and OWL which may attain the required order of magnitude increase in sensitivity [34].

The cosmic neutrino flux can be much higher than the conservative benchmark values we have adopted above. Data from HiRes [31] suggest that it may be [30] just below the current experimental bound from AMANDA-B10 [35]. The expected event rates in Auger itself would then be high enough to test for any suppression of the UHE $\nu - N$ cross-section. Since the spectrum in this case is softer than the WB flux, IceCube [2], with its lower energy threshold, should test this model very soon. Indeed IceCube has the sensitivity to see the benchmark WB flux within a few years. Thus there is an emerging synergy between large cosmic ray arrays and cosmic neutrino detectors which will soon establish if there is a realistic possibility for exploring fundamental physics using Nature's own high energy beams. Given that there is no conceivable terrestrial accelerator which can attain such energies, we believe that the construction of Super Auger should be considered seriously; the detection techniques are well developed and the resources required are no larger than for a contemporary collider experiment.

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