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Particle Physics on Ice: Constraints on Neutrino Interactions Far above the Weak Scale

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Ultrahigh energy cosmic rays and neutrinos probe energies far above the weak scale. Their usefulness might appear to be limited by astrophysical uncertainties; however, by simultaneously considering up- and down-going events, one may disentangle particle physics from astrophysics. We show that present data from the AMANDA experiment in the South Pole ice already imply an upper bound on neutrino cross sections at energy scales that will likely never be probed at man-made accelerators. The existing data also place an upper limit on the neutrino flux valid for any neutrino cross section. In the future, similar analyses of IceCube data will constrain neutrino properties and fluxes at the $\mathcal{O}(10\%)$ level.

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Ultrahigh energy cosmic rays have been observed with energies above 10^{10} GeV, implying collisions with terrestrial protons at center-of-mass energies above 100 TeV. Ultrahigh energy cosmic neutrinos, so far undetected, are expected to accompany these cosmic rays. These cosmic neutrinos are especially interesting, because their known interactions are so weak that they are highly sensitive to new interactions at energies far above the weak scale, where new interactions are expected in many extensions of the standard model (SM) of particle physics. In addition, ultrahigh energy neutrinos are unique messengers, as they are expected to escape from (and point back to) even the most dense astrophysical sources.

The promise of ultrahigh energy neutrinos might appear to be severely limited by astrophysical uncertainties. Event rates constrain only a combination of fluxes and cross sections, and so astrophysical uncertainties cloud particle physics implications and vice versa. However, the event rates for up- and down-going neutrinos depend differently on neutrino cross sections [1,2]. By combining both up- and down-going data one may therefore disentangle particle physics from astrophysics and constrain both the properties of astrophysical sources and the interactions of neutrinos far above the weak scale.

Here we consider neutrino telescopes operating under ice at the South Pole [3,4]. We show that current data from the AMANDA South Pole telescope [5] already significantly constrain neutrino cross sections at center-of-mass energies $\sqrt{s} \approx 6$ TeV, and future data will provide $\mathcal{O}(10\%)$ determinations. These results will be complemented [6] by future data from the Pierre Auger Observatory [7]. The energies probed are far above the HERA domain $\sqrt{s} \simeq 500$ GeV, the highest accelerator energy at which even indirect tests of neutrino cross sections have been made.

Simple parton model predictions for neutrino-nucleon cross sections [8] may be suppressed, for example, by saturation effects at small x [9]. Such effects have been proposed to slow down the power law scaling of cross section with neutrino energy to comply with the Froissart bound [10]. On the other hand, neutrino cross sections may also be enhanced, for example, by the exchange of towers of Kaluza-Klein gravitons [11], black hole production [2,12], TeV-scale string excitations [13], or electroweak instanton processes [14]. Our results constrain all of these possibilities.

The results derived below also constrain the extraterrestrial neutrino flux, which is at present unknown. Neutrino sources may be conveniently characterized as either optically thin or thick. In optically thin sources, the nucleons responsible for neutrino production (through photoproduction or pp collisions) escape the source and constitute the observed cosmic rays. The observed cosmic ray and diffuse neutrino fluxes are then correlated [15]. In contrast, in optically thick sources, the neutrino progenitors do not escape, thus vitiating the relation between cosmic ray and neutrino fluxes [16]. In principle, this permits a very large enhancement to the neutrino flux. We derive upper bounds on this enhancement that are valid for any neutrino cross section.

We will derive bounds without assuming particular neutrino fluxes or cross sections. It will be convenient, however, to present results relative to standard reference values. For the reference cross section, we choose $\sigma_{\rm SM}$, the charged current (CC) neutrino-nucleon cross section of the simple parton model [8]. For the reference flux, we adopt the Waxman-Bahcall (WB) flux $\phi_{\rm WB}^{\nu}$ [15]. This flux is that of an optically thin source. At production, the WB flux has flavor ratios $\nu_\mu : \nu_e : \nu_\tau = 2:1:0$, but this quickly transforms to 1:1:1 through neutrino oscillations, and so $E^2 \phi_{\rm WB}^{\nu} \simeq 2 \times 10^{-8}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ for each flavor. In what follows, we focus on neutrino energies in the range 10^7 GeV to $10^{7.5}$ GeV, where the background from atmospheric neutrinos is negligible, but the extraterrestrial flux is expected to be significant. Hereafter, we take $\langle E \rangle = 10^{7.25}$ GeV.

Neutrinos are detected in neutrino telescopes when they create charged leptons or showers through CC or neutral current (NC) events near the neutrino telescope, and the resulting leptons or showers propagate into the experiment's instrumented volume. For down-going events, the probability of neutrino conversion is always small, barring extraordinary enhancements to neutrino cross sections. Letting $\sigma_{\nu N}$ denote the total (NC + CC) neutrino-nucleon cross section, the down-going event rate is therefore

$$\mathcal{N}_{\rm down} = C_{\rm down} \frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma_{\nu N}}{\sigma_{\rm SM}}, \tag{1}$$

where ϕ^ν indicates the average extraterrestrial $\nu + \bar{\nu}$ flux per flavor in the energy bin of interest. The constant $C_{\rm down}$ depends on exposure and acceptance and varies according to neutrino flavor from experiment to experiment.

For up-going events, the dependence on cross section is completely different. At energies above 10^6 GeV, neutrino interaction lengths become smaller than the radius of the Earth. For ν_e and ν_μ, this implies that most upward-going neutrinos are shadowed by the Earth, and only those that are Earth-skimming [17], traveling at low angles along chords with lengths of order their interaction length, can produce a visible signal. For ν_τ, this attenuation is somewhat offset by effects of regeneration $\nu_\tau \to \tau \to \nu_\tau$ [18]. However, in the energy range of interest, the expected events will be largely dominated by neutrinos surviving until the region of the detector.

The dependence of upward-going event rates on anomalous neutrino cross sections depends on the source of the anomaly. We consider two prominent cases. First, in many new physics cases, the SM CC cross section $\sigma_{\rm SM}$ is not altered, but there are new neutrino interactions that produce showers. Letting $\sigma_{\nu N}$ be the total neutrino cross section, including the standard model CC and new physics contributions, the up-going event rate is [6]

$$\mathcal{N}_{\rm up} = C_{\rm up} \frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma^2_{\rm SM}}{\sigma^2_{\nu N}} \quad \left(\frac{\sigma_{\nu N}}{\sigma_{\rm SM}} > 1\right). \tag{2}$$

As discussed in Ref. [6], Eq. (2) is valid assuming $L^l \ll L^\nu < R_\oplus$, where L^l is the typical lepton path length in Earth, L^ν is the neutrino interaction length in Earth, and $R_\oplus$ is the radius of the Earth. This corresponds to $E > 10^7$ GeV. Here, $\sigma_{\nu N}$ indicates any enhancement of the cross section which will increase the event rate for down-going neutrinos, but because of absorption will suppress the upcoming events. The latter can be achieved through cuts on shower energy fraction greater than or equal to that characterizing the CC SM process. Extreme enhancements to $\sigma_{\nu N}$ may reduce L^ν to L^l, leading to a different parametric dependence in Eq. (2), but we neglect such cases here. Second, we consider the possibility of screening, in which both the standard model NC and CC cross sections are reduced equally. In this case [1,6],

$$\mathcal{N}_{\rm up} = C^{\rm screen}_{\rm up} \frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma_{\rm SM}}{\sigma_{\nu N}}, \tag{3}$$

where $\sigma_{\nu N}$ and $\sigma_{\rm SM}$ are CC cross sections with and without screening, respectively.

Given the parametric dependences of Eqs. (1)–(3), we now consider the implications of existing data from AMANDA. Assuming the standard model CC neutrino interaction, the AMANDA Collaboration has derived the 90% C.L. upper bound on the diffuse neutrino flux $E^2\phi^\nu_{\rm max} = 3.3 \times 10^{-7}\ {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ per flavor [5], assuming an E^{-2} dependence of the flux, valid for 10^6 GeV to $10^{9.5}$ GeV neutrinos. Since the energy distribution of the AMANDA data peaks in the energy bin of interest, it is reasonable to use $\phi^\nu_{\rm max}(\langle E\rangle)$ as the upper limit in the bin. Here we generalize this bound to the case in which there are *two* unknown quantities: the neutrino cross section and the neutrino flux. Applied to ν_e down-going events, the constraint implies

$$\phi^\nu \frac{\sigma_{\nu N}}{\sigma_{\rm SM}} < \phi^\nu_{\rm max}. \tag{4}$$

Dividing Eq. (4) by $\phi^\nu_{\rm WB}$ gives

$$\frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma_{\nu N}}{\sigma_{\rm SM}} < 16 \tag{5}$$

at 90% C.L. A similar analysis for up-going events yields

$$\frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma^2_{\rm SM}}{\sigma^2_{\nu N}} < 16 \quad \left(\frac{\sigma_{\nu N}}{\sigma_{\rm SM}} > 1\right) \tag{6}$$

for the case of new physics contributions, and

$$\frac{\phi^\nu}{\phi^\nu_{\rm WB}} \frac{\sigma_{\rm SM}}{\sigma_{\nu N}} < 16 \tag{7}$$

for the case of screening.

These constraints exclude the shaded regions of Fig. 1. The upper region is excluded by down-going data and the lower region is excluded by the up-going data, assuming screening. The upper and lower regions meet at $\sigma_{\nu N}/\sigma_{\rm SM} = 1$. As a result, for any neutrino cross section, we find an upper bound on the neutrino flux in the energy range 10^7 GeV to $10^{7.5}$ GeV of $\phi^\nu < 16\phi^\nu_{\rm WB}$. Note that the lower shaded region limits the amount by which screening effects can suppress $\sigma_{\rm SM}$.

How will these results improve in the near future? We now consider the possible implications of IceCube, the successor experiment to AMANDA. In the energy range of interest the τ decay length is comparable to the instrumented volume; thus, one can observe all ν_τ topologies: a τ track followed by the τ-decay shower ("lollipop"), a hadronic shower followed by a τ track which leaves the detector ("popillol"), and double bang events. All of these distinctive topologies allow a direct and precise measurement of the incoming neutrino energy [19]. We also note that the absence of oscillation precludes a ν_τ atmospheric background. For these reasons, the detection prospects for up-going neutrinos are brighter for ν_τ than the other flavors, and we focus on them below.

To evaluate the prospects for IceCube, we must determine $C_{\rm down}$ and $C_{\rm up}$ for IceCube. We focus on the case in which new neutrino interactions modify the NC cross sections, but leave the CC cross sections invariant. In NC processes most of the energy is carried off by pions. At TeV energies, the interaction mean free path of $\pi^\pm$ in ice is orders of magnitude smaller than the pion decay length, and so nearly all energy is channeled into electromagnetic modes through π^0 decay. To estimate the efficiencies for down-going events in the NC channel, we therefore adopt as our basis of comparison the electromagnetic showers induced by ν_e [20]. With this in mind,

$$C_{\rm down} = 2\pi \phi^\nu_{\rm WB} \sigma_{\rm SM} N_{\rm T} T \Delta E \int_0^1 \eta(\cos\theta) d\cos\theta, \qquad (8)$$

where $N_{\rm T}$ is the number of target nucleons in the effective volume, $0.5 < \eta(\cos\theta) < 1$ is the experimental efficiency for detection of electron neutrino showers with zenith angle θ, T is the running time, and $\Delta E = 2.2 \times 10^7$ GeV.

IceCube is now under construction, in the process of growing to its final size. Including absorption effects, it will have an effective aperture $(A\Omega)_{\rm eff} \sim \pi/2$ km^2 sr for detecting ν_τ [4]. The detector will consist of 80 km-length strings, each instrumented with 60 optical modules. The number of target nucleons may therefore be estimated to be $N_{\rm T} \simeq 6 \times 10^{38}$. To remain conservative, we take $\int_0^1 \eta(\cos\theta) d\cos\theta = 0.8$. Inserting these numbers into Eq. (8), along with a lifetime of the experiment $T = 15$ yr and $\sigma_{\rm SM}(\langle E \rangle) \simeq 2 \times 10^{-33}$ cm^2 [8], we obtain $C_{\rm down} \simeq 4$. The corresponding quantity for up-going events in our energy interval is $C_{\rm up} = (A\Omega)_{\rm eff} T \int \phi^\tau(E) dE \simeq 20$, where $\int \phi^\tau(E) dE = 8.5 \times 10^{-1}$ km^{-2} yr^{-1} sr^{-1} is the τ-lepton flux emerging from the Earth due to (unabsorbed) ν_τ interactions inside the Earth for incoming $\phi^\nu = \phi^\nu_{\rm WB}$ and $\sigma_{\nu N} = \sigma_{\rm SM}$ [21].

Given these estimates of $C_{\rm down}$ and $C_{\rm up}$, we now determine projected sensitivities of IceCube to neutrino fluxes and cross sections. For a given set of observed rates $\mathcal{N}^{\rm obs}_{\rm up}$ and $\mathcal{N}^{\rm obs}_{\rm down}$, two curves are obtained in the two-dimensional parameter space by setting $\mathcal{N}^{\rm obs}_{\rm up} = \mathcal{N}_{\rm up}$ and $\mathcal{N}^{\rm obs}_{\rm down} = \mathcal{N}_{\rm down}$. These curves intersect at a point, yielding the most probable values of flux and cross section for the given observations. Fluctuations about this point define contours of constant χ^2 in an approximation to a multi-Poisson likelihood analysis [22].

In Fig. 1, we show results for two representative cases that are consistent with the AMANDA bounds derived above. In the first case, we assume $\sigma_{\nu N} = \sigma_{\rm SM}$ and $\phi^\nu = \phi^\nu_{\rm WB}$, leading to 4 down-going and 20 up-going events. The 90%, 99%, and 99.9% C.L. contours are those given in the lower left of the figure. [These contours will be slightly distorted for $\sigma_{\nu N}/\sigma_{\rm SM} < 1$, where Eq. (2) receives corrections, but we neglect this effect.] We see that, even in the case that event rates are in accord with standard assumptions, the neutrino-nucleon cross section is bounded to be within 40% of the SM prediction at 90% C.L. This is at a center-of-mass energy $\sqrt{s} \simeq 6$ TeV, far beyond the reach of any future man-made accelerator [23]. In the second case, we consider a scenario in which the number of observed upcoming events remains at 20, but the number of down-going events is 35. In the second case, clearly one has discovered new physics at well beyond 5σ.

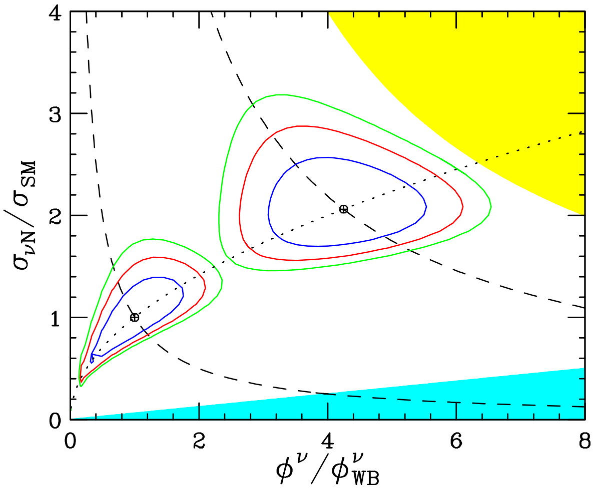

FIG. 1 (color online). Projected determinations of neutrino fluxes and cross sections at $\sqrt{s} \approx 6$ TeV from future IceCube data. Two cases with $(\mathcal{N}^{\rm obs}_{\rm down}, \mathcal{N}^{\rm obs}_{\rm up}) = (4, 20)$ and $(35, 20)$ are considered. In both cases, the best fit flux and cross sections are shown, along with the 90%, 99%, and 99.9% C.L. inclusion contours. Contours of constant $\mathcal{N}_{\rm up} = 20$ (dotted line), $\mathcal{N}_{\rm down} = 4$ (left dashed line), and $\mathcal{N}_{\rm down} = 35$ (right dashed line) are also shown. Neutrino fluxes and cross sections excluded by AMANDA at 90% C.L. are also indicated: The upper (lower) shaded region is excluded by null results for down-going (up-going) events [5].

It is noteworthy that in the energy bin of interest, the predicted [24] diffuse flux of neutrinos from a uniform distribution of blazars, $\phi^\nu_{\rm AGN}(E)$, is about 9 times larger than the WB flux, i.e., $\phi^\nu_{\rm AGN}(\langle E \rangle) \simeq 9\phi^\nu_{\rm WB}$. These neutrinos are expected to be produced in optically thick cores of blazars when ultrahigh energy protons scatter off the accretion disk orbiting the active galactic nucleus (AGN) [25]. By rescaling the integrated luminosity in Eqs. (1) and (2), it is straightforward to see that if the extraterrestrial flux is at the $\phi^\nu_{\rm AGN}$ level, in 2 yr of operation IceCube will probe 40% (70%) enhancements from SM predictions at the 90% (99.9%) C.L.

Finally, we note that the AMANDA constraints have significant consequences for what may be seen at IceCube. Substituting Eq. (5) into Eq. (1) with $C_{\rm down}$ determined for IceCube, the ν_e down-going event rate in the energy range 10^7 GeV to $10^{7.5}$ GeV is constrained to $\mathcal{N}_{\rm down} < 4$ yr^{-1} at 90% C.L. [26]. Event rates at IceCube for low scale gravity models have been presented [27]. These event rates, along with this bound on $\mathcal{N}_{\rm down}$, can be used to constrain the multidimensional Planck scale.

In summary, we have shown that the sensitivity of neutrino telescopes in the Antarctic ice to both up- and down-going ultrahigh energy neutrinos provides a powerful probe of ultrahigh energy neutrino fluxes and anomalous neutrino interactions. Current null results from AMANDA already provide interesting constraints on the flux cross section parameter space. First, these results constrain both suppressions of the neutrino flux from putative screening effects and enhancements from new physics. Second, they exclude large fluxes $\phi^\nu > 16\phi^\nu_{\rm WB}$ for neutrino energies between 10^7 GeV and $10^{7.5}$ GeV, for any neutrino cross section. These energies correspond to neutrino-nucleon collisions at $\sqrt{s} \approx 6$ TeV, far above the weak scale and likely never to be accessible at man-made accelerators.

In the future, IceCube will be able to determine both neutrino fluxes and cross sections with impressive accuracy. We have considered neutrinos with energies between 10^7 GeV and $10^{7.5}$ GeV. For standard model cross sections and the WB flux, 40% (70%) enhancements from standard model predictions may be excluded at 90% (99.9%) C.L. in 15 years of running. Should the neutrino flux be at the level predicted for optically thick blazars, these bounds can be attained after two years of data collection at IceCube. Our analysis assumes an extraterrestrial neutrino flux with 1:1:1 flavor composition. If IceCube finds a different flavor mix [28], it will not be difficult to repeat this analysis for the correct flavor ratios.

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