Limits on Topological Defect Neutrino Fluxes from Horizontal Air Shower Measurements

J. J. Blanco-Pillado,[1] R. A. Vázquez,[1,2] and E. Zas[1]
[1]*Departamento de Física de Partículas, Universidad de Santiago, E-15706 Santiago de Compostela, Spain*
[2]*INFN sez. di Roma and Universitá della Basilicata, Italy*
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We obtain the horizontal air shower rate from the (EeV) high energy neutrino flux predicted in some topological defect scenarios as the source for the highest energy cosmic rays. Emphasis is made on the different character of the events depending on the neutrino flavor and type of interaction. We show that the bound for muon poor showers in the 10^5-10^7 GeV energy range is violated by maximal predictions for superconducting cosmic string neutrino fluxes, we compare it to other neutrino flux limits, and we discuss the future of such measurements to further constrain these models. [S0031-9007(97)03017-2]

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The establishment of cosmic rays of energies above 10^{20} eV [1] and the prospects for the construction of a giant air shower array for their study, the Pierre Auger project [2] have stimulated great activity in the search of theoretical models for the production of these particles. The annihilation of topological defects (TD's) has been recently proposed as the origin of the highest energy cosmic rays [3], although there is some controversy about this possibility [4]. This mechanism avoids the main difficulties in the conventional shock acceleration and would imply large fluxes of gamma rays and neutrinos up to energies in the EeV range and well above [5]. Active galactic nuclei (AGN), the most powerful known objects, have also been suggested as the possible origin of the highest energy cosmic rays [6]. If the very high energy gamma rays detected from AGN [7] come from pion decay, in proton acceleration models, they must also emit high energy neutrinos. Models for acceleration in the AGN jets predict neutrinos also extending to the EeV range [8–11].

Some of these models have already been shown to predict secondary photon and neutrino fluxes in conflict with experiment. TD models are significantly constrained by the observations of the diffuse gamma ray flux in the 100 MeV region [12]. Also the Frèjus underground muon detector has not observed the muon neutrino prediction for superconducting cosmic strings (SCS) [13]. Clearly, there are many uncertainties in these models such as the normalization, the mass of the X particle in the grand unified theory (GUT) scale M_X, the extragalactic magnetic field, the fragmentation functions involved, as well as the propagation of each of the produced particles in the extragalactic magnetic field and background radiations, taking into account the evolution of the Universe. While some authors disfavor [14] or even claim to rule out these models as the source of the highest energy cosmic rays [15], others argue that tuning the free parameters in the model (M_X, the maximum of the injection spectrum and the extragalactic magnetic field), it is still possible to explain the ultrahigh energy (UHE) cosmic events, avoiding the 100 MeV gamma ray constraints [16].

Large scale high energy neutrino detectors are expected to further test these models [6]. As the Earth becomes opaque for neutrinos already in the 100 TeV to 1 PeV range, EeV neutrinos can be detected only for zenith angles between vertical down going and horizontal. In such a case the experiment must have some control over the energy of the muon to separate the neutrino signal from that of atmospheric muons, which poses a serious background. Underground muon experiments rely on their overburden for this purpose. For high energies they must search for close to horizontal neutrinos where the overburden and energy uncertainties are largest. Detectors in water or ice may, in addition, detect Cerenkov light from neutrino showers with the advantage of being also sensitive to the electron neutrino. They require good directional and shower reconstruction capabilities to separate neutrino showers from those induced by muons. Horizontal air shower (HAS) measurements provide a third alternative as they are due to high energy penetrating particles such as muons and neutrinos [17] (including electron neutrinos), and shower size determinations can be used as an energy threshold. Existing air shower arrays can constrain neutrino fluxes [18,19], and their relevance for direct neutrino detection will become more important when the Pierre Auger project is constructed [20,21].

In this paper we calculate the HAS rate due to neutrino fluxes from TD and recent AGN models separating explicitly the muon poor HAS in order to compare it to the bound published by the AKENO group [22]. For TD models we take two models, $p = 0$ and $p = 0.5$ in Ref. [23], corresponding to two different injection rates. The $\nu_e + \overline{\nu}_e$ flux prediction in the maximal superconducting string model violates this bound. We compare the different shower channels in this model showing that about half the total $\nu_e + \overline{\nu}_e$ contribution is muon poor. The muons produced by charged current muon neutrino interactions in the atmosphere dominate the "standard" atmospheric muon flux at high energies and we calculate the HAS contribution from secondary bremsstrahlung from these muons. This is the dominant contribution to muon poor showers from $\nu_\mu + \overline{\nu}_\mu$. We finally compare the

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AKENO bound to other bounds emphasizing the differences in energy range, and we briefly address the potential capabilities of typical existing and planned air shower arrays to detect neutrino induced horizontal showers.

Horizontal air showers.—HAS have been observed in the 1960s by several groups for shower sizes between 10^3–10^5 particles [24]. The shower rate observed is consistent with conventional muon production by hard bremsstrahlung [18,24–26]. For shower sizes above 10^5 particles, AKENO has published an upper bound on muon poor air showers at zenith angles greater than 60° [22].

There are multiple shower channels for neutrino showers. Deep inelastic scattering (DIS) interactions of the neutrino with air nucleons via charged and neutral currents produce a hadronic shower of energy yE_ν, where y is the energy fraction transferred to the nucleon. In charged current electron-neutrino (antineutrino) interactions the emitted electron (positron) generates an electromagnetic cascade carrying the remaining energy of the initial neutrino $(1 - y)E_\nu$ that is superimposed to the cascade initiated by the hadron debris. For muon neutrinos the charged current interaction produces a secondary flux of high energy muons which could in turn induce horizontal showers further into the atmosphere in the same way atmospheric muons do. The interaction of neutrinos with atomic electrons is in general suppressed by the ratio of the electron to the proton rest mass except for the Glashow resonance $\overline{\nu}_e + e^- \rightarrow W^-$, which dominates over all other processes at the resonance energy $E_{\overline{\nu}_e} \sim 6.4 \times 10^6$ GeV [27]. The decay of the W boson into an electron and an antineutrino generates a purely electromagnetic shower with energy $E \sim 3 \times 10^6$ GeV. Its decay in the muon channel will also contribute to the horizontal muon flux at these energies, while the tau channel will in turn decay into hadrons 64% of the times and into a muon or an electron 18% of the times each.

Following Ref. [18] the differential rate of horizontal cascades at fixed shower size N_e, is obtained similarly for neutrinos and muons integrating the parent flux, the y differential cross section of the corresponding interaction and the atmospheric depth

$$\phi_{sh}(N_e) = \int_0^\infty dt \int_0^1 \frac{dy}{\overline{y}}\, \phi_{\nu,\mu} \times \left[E_{\nu,\mu} = \frac{E(N_e,t)}{\overline{y}} \right] \frac{d\sigma}{dy}\, \frac{dE}{dN_e}. \quad (1)$$

Here $\overline{y}$ is y, $1 - y$, or 1 depending on the interaction that produces the shower. For muon bremsstrahlung the energy of the photon which originates a shower at a given depth and of a given shower size is determined, on average, by the inverse of the Greisen parametrization $E(N_e, t)$ [28]. The energy of the parent muon is given by E/y. The factor dE/dN_e is just the Jacobian of the transformation. For neutral current interactions the energy of the hadron debris is inferred inverting the parametrization of hadronic showers due to Gaisser [29]. In the case of charged current electron neutrino interactions, Eq. (1) applies with $\overline{y} = 1$, because all the energy is transferred to the shower; and a more complicated shower size depending on y and combining both parametrizations has been used. The expression neglects shower fluctuations. While first point interaction fluctuations are irrelevant for the neutrino calculation shower size fluctuations will enhance the horizontal shower rate for a spectrum that drops in energy. For typically flat TD fluxes, the corrections are, however, small [30].

We have performed the previous calculations using the neutrino flux predictions from topological defects [23] and from AGN models [9], and we have assumed that the fluxes for ν_e, $\overline{\nu}_e$, ν_μ, and $\overline{\nu}_\mu$ are in the ratio 1:1:2:2. In Fig. 1 we show the $\nu_\mu + \overline{\nu}_\mu$ differential fluxes in these models compared to atmospheric neutrinos. For the neutrino cross section we have used the MRS(G) parton distribution functions [31] extrapolated to low x as described in [20]. We have checked that our results are not sensitive to using alternative parametrizations for shower size such as that of Fenyves *et al.* [32], nor to the multiplicity of hadrons in the DIS interactions. In Fig. 2 we show the total integral horizontal air shower rates for the TD and AGN models as a function of the shower size, compared to Tokyo data [24] and to expectations from atmospheric muons.

Muon poor showers.—The AKENO bound on horizontal air showers has been obtained on the basis of searching for muon poor showers. This has allowed the search for showers of zenith angle already above 60° but it means that only the muon poor fraction of the HAS produced by a hypothetical neutrino flux has to be compared with this bound. Electron-neutrino charged current interactions in which the hadronic component carries less than the 20% of the initial energy $E_\nu(y < 0.2)$ produce muon poor showers according to AKENO requirements. Since the average $\langle y \rangle$ at high energies approaches 0.2 [27] a good fraction of

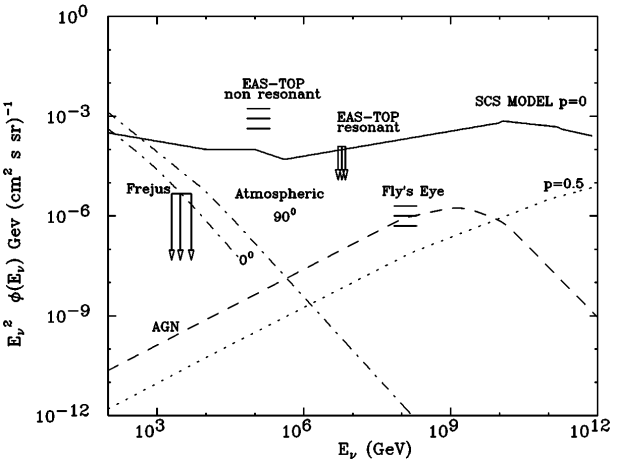

FIG. 1. Differential $(\nu_\mu + \overline{\nu}_\mu)$ fluxes of Ref. [23] for $p = 0$ (solid line) and for $p = 0.5$ (dotted). The dashed line is the prediction of Ref. [8] and the dot-dashed line is the atmospheric flux. Also shown are some published limits as marked. The three parallel lines illustrate the change in the limits for different spectral indices (1.1, 2, and 3 from bottom to top).

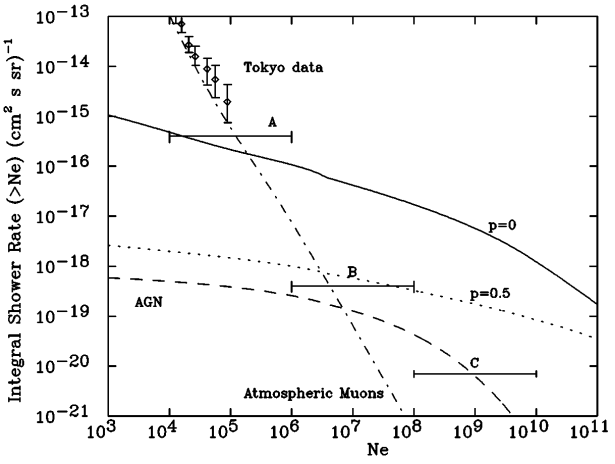

FIG. 2. Integral horizontal shower rate as a function of shower size (N_e) for different models. TD neutrinos with $p = 0$ (solid line), $p = 0.5$ (dotted), AGN neutrinos (dashed), and atmospheric muons (dot-dashed). Diamonds represent the HAS data from Ref. [24]. Horizontal lines marked as *A*, *B*, and *C* represent the expected limit of nonobservation in a year made with ideal detectors of areas 10^5 m^2 (*A*), 10^8 m^2 (*B*), and 10^{10} m^2 (*C*). See text.

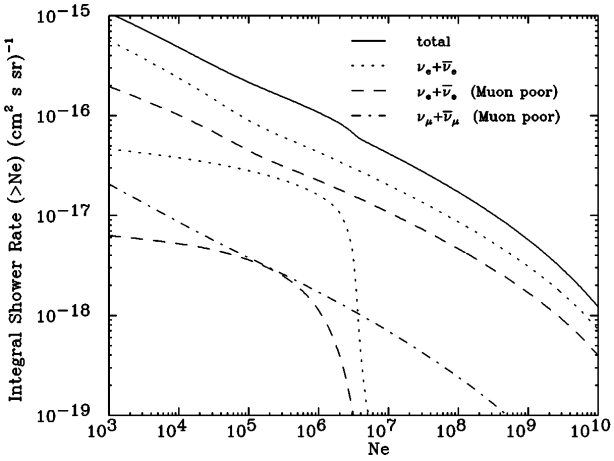

FIG. 3. Partial HAS channels for the TD model with $p = 0$. From top to bottom: Total rate, ($\nu_e + \overline{\nu}_e$) DIS contribution, the muon poor ($\nu_e + \overline{\nu}_e$) DIS contribution, the total resonant contribution ($\overline{\nu}_e$), the secondary muon bremsstrahlung, and the resonant contribution into the electron channel.

the electron neutrino showers are muon poor. Both these contributions are calculated as described in the previous section. For the SCS model we compare the total rate of HAS to that from electron neutrinos and antineutrinos only, separating the DIS and the resonant contributions in Fig. 3. We also plot in the same figure the results for muon poor horizontal showers as described above separating the resonant and DIS channels as well. Of all the electron neutrino HAS, about 50% are muon poor at high energies.

Any channel for producing muons can also give pure electromagnetic showers through secondary muon bremsstrahlung or electron positron production. In spite of the suppression due to a double process, its contribution can be relevant for muon poor showers at large zenith angles. We consider muons produced in charged current muon-neutrino interactions and those produced in the resonant interaction decaying into a muon and a muon antineutrino, these muons carry most of the energy of the interaction. Muons produced in hadronic showers or tau decays have lower energy and can be neglected in comparison to other uncertainties.

For incoming muon neutrinos, we have first calculated the muon flux produced by the charged current interaction of horizontal muon neutrino fluxes through the 36 000 g cm^{-2} slant depth. This flux will give rise to purely electromagnetic horizontal showers due to hard processes of energy loss such as bremsstrahlung and electron positron production. These showers will generally develop well after the first shower initiated by the nucleon debris is absorbed. The calculation of this channel uses Eq. (1) with the secondary muon flux, the muon cross section, and $\overline{y} = y$. We consider the dominant contribution, bremsstrahlung, and we use the cross section given by [33]. The shower rate calculated in this way at 90° represents approximately 50% of the "direct" electron neutrino showers with a cut in $y < 0.2$. Secondary bremsstrahlung is the most important channel for muon poor showers induced by muon neutrinos and has a strong dependence on zenith angle. The result of secondary muon bremsstrahlung HAS in the SCS model, averaged over the zenith angles from 60° to 90°, is also compared to the other channels in Fig. 3. The contribution represents less than a 10% effect on the total number of muon poor showers because of this averaging.

In Fig. 4 we display the results for muon poor showers in the considered models together with the AKENO bound where it is shown how the model with $p = 0$ is ruled out by an ample margin. The figure also illustrates how the model with different time evolution ($p = 0.5$) is not far from being tested with current experiments assuming improvements in statistics. We have included in Fig. 2 a rough theoretical estimate of the 90% confidence upper limit for no observations during a year. We assume no ordinary cosmic ray showers penetrate at angles above 75° and ideal air shower arrays of three areas $\sim 10^5$ m^2, $\sim 10^2$ km^2, and $\sim 10^4$ km^2. These are typical order of magnitude sizes of existing and planned arrays.

Limits.—The information provided by Frèjus, HAS, and Fly's Eye, ruling out the same types of models, is complementary in the sense that they relate to very different parts of the neutrino spectrum and because HAS apply to electron neutrinos as well. It is interesting to compare the limit derived from the AKENO bound with other limits for high energy neutrino fluxes. At lower energies ($\sim$3 TeV), the Frèjus limit [13] rules out the TD prediction with $p = 0$. The Fly's Eye limit [19] also rules out this prediction at much higher energies $\sim 10^5$ TeV. The limit from AKENO lies in between, in the PeV region. The EAS-TOP Collaboration [34] has

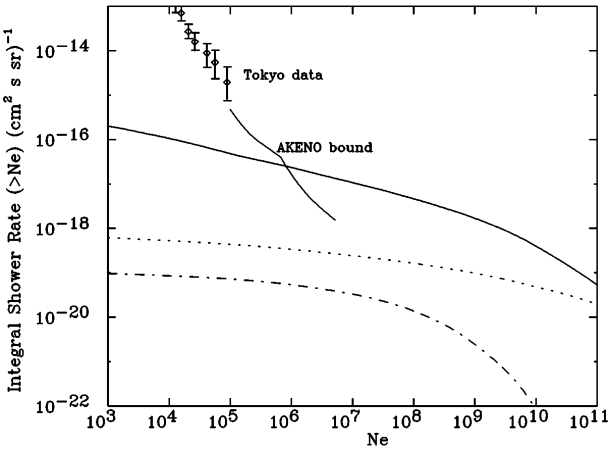

FIG. 4. Muon poor integral shower rate for the three models. TD $p = 0$ (solid line), $p = 0.5$ (dotted), and AGN (dashed).

also published a less constraining limit on high energy neutrino fluxes from horizontal showers also near the PeV region. In Fig. 1 we show the flux predictions together with these limits. This figure, however, must be interpreted with care as these limits can be very flux dependent. We illustrate this by plotting the limits corresponding to constant spectral index fluxes with different indices ($\gamma = 1.1, 2, 3$). In this respect it would be useful that all experiments measuring air showers such as EAS-TOP, CYGNUS, and Fly's Eye (measuring upcoming showers), gave their results as air shower rates like AKENO as this would simplify the comparisons between experiments and would be a step forward to the establishment of these results.

HAS (within which we include Fly's Eye results) are a tool for constraining TD scenarios via the neutrino-induced showers produced along with the UHE cosmic rays, and they rule out the superconducting cosmic string model normalized to the highest energy cosmic ray spectrum [23] in agreement with Ref. [15]. The prospects of running the largest existing air shower arrays using horizontal triggers, in order to get not only the electromagnetic shower rate bounds, but the rate of all horizontal air showers, should further constrain the present TD models. Clearly, the possibility of searching for HAS with future air shower arrays such as the Pierre Auger Project, with an area about 60 times larger than AKENO, if viable, would undoubtedly provide a much stronger constraint on these models.

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