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High Energy Neutrinos with a Mediterranean Neutrino Telescope

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Abstract: The high energy neutrino detection by a km^3 Neutrino Telescope placed in the Mediterranean sea provides a unique tool to both determine the diffuse astrophysical neutrino flux and the neutrino-nucleon cross section in the extreme kinematical region, which could unveil the presence of new physics. Here is performed a brief analysis of possible NEMO site performances.

Introduction

Neutrinos are one of the main components of the cosmic radiation in the high energy regime. Although their fluxes are uncertain and depend on the production mechanism, their detection can provide information on the sources and origin of the high energy cosmic rays.

From the experimental point of view the detection perspectives are stimulated by the Neutrino Telescopes (NT's) constructed, like `Baikal` [1] and `AMANDA` [2], or under construction like `IceCube` [3] under the ice and `ANTARES` [4] in the deep water of the Mediterranean sea. Here, also the experiments `NESTOR` [5] and `NEMO` [6] are in the R&D phase and, together with `ANTARES`, in the future could lead to the construction of a km^3 telescope as pursued by the `KM3NeT` project [7].

Although NT's were originally thought as ν_μ detectors, their capability as ν_τ detectors has become a hot topic in view of the fact that flavor neutrino oscillations lead to nearly equal astrophysical fluxes for the three neutrino flavors. Despite the different behavior of the produced tau leptons with respect to muons in terms of energy loss and decay length, both ν_μ and ν_τ event detection rates are sensitive to the matter distribution near the NT area. In principle, the elevation profile of the Earth surface around the detector may be relevant. In Ref. [8], some of the present authors calculated the aperture of the Pierre Auger Observatory [9] for Earth-skimming UHE ν_τ's, by using the Digital Elevation Map (DEM) of the site (GTOPO30) [10]. In Ref. [11] the DEM's of the under-water Earth surface, provided by the Global Relief Data survey (ETOPO2) [12], was used to estimate the effective aperture for ν_τ and ν_μ detection of a km^3 NT in the Mediterranean sea placed at any of the three locations proposed by the `ANTARES`, `NEMO` and `NESTOR` collaborations. In the present paper we further develop the approach of Ref. [11] to evaluate the performances of a Mediterranean NT in the simultaneous determination of the neutrino flux and the ν-Nucleus cross section in extreme kinematical regions (which may probe new physics, see e.g. [13]). Since the three different proposed sites for the under-water km^3 telescope show event rate differences of the order of 20%, for the sake of brevity we report the results our analysis for the `NEMO` site only, which presents intermediate performances.

Formalism and results

Following the formalism developed in [8, 11] we define the km^3 NT *fiducial* volume as that bounded by the six lateral surfaces Σ_a (the index a=D, U, S, N, W, and E labels each surface through its orientation: Down, Up, South, North, West, and East), and indicate with $\Omega_a \equiv (\theta_a, \phi_a)$ the generic direction of a track entering the surface Σ_a (see Figure 4 of Ref. [11] for notations). We introduce all relevant quantities with reference to ν_τ events, the case of ν_μ being completely analogous.

Let $\mathrm{d}\Phi_\nu/(\mathrm{d}E_\nu\,\mathrm{d}\Omega_a)$ be the differential flux of UHE $\nu_\tau + \bar{\nu}_\tau$. The number per unit time of τ leptons emerging from the Earth surface and entering the NT through Σ_a with energy E_τ is given by

$$\left(\frac{\mathrm{d}N_\tau}{\mathrm{d}t}\right)_a = \int \mathrm{d}\Omega_a \int \mathrm{d}S_a \int \mathrm{d}E_\nu \, \frac{\mathrm{d}\Phi_\nu(E_\nu, \Omega_a)}{\mathrm{d}E_\nu\,\mathrm{d}\Omega_a} \int \mathrm{d}E_\tau \; \cos(\theta_a)\, k_a^\tau(E_\nu, E_\tau; \vec{r}_a, \Omega_a). \quad (1)$$

The kernel $k_a^\tau(E_\nu\,, E_\tau\,; \vec{r}_a, \Omega_a)$ represents the probability that an incoming ν_τ crossing the Earth, with energy E_ν and direction Ω_a, produces a τ-lepton which enters the NT fiducial volume through the lateral surface $\mathrm{d}S_a$ at the position $\vec{r}_a$ with energy E_τ. For an isotropic flux and an exposure time T, the total number of τ leptons (and similarly for muons) crossing the NT is

$$N_\tau = T \sum_a \int \mathrm{d}\Omega_a \int \mathrm{d}S_a \int \mathrm{d}E_\nu \int \mathrm{d}E_\tau \left(\frac{1}{4\pi}\,\frac{\mathrm{d}\Phi_\nu(E_\nu)}{\mathrm{d}E_\nu}\right) \cos(\theta_a)\; k_a^\tau(E_\nu\,, E_\tau\,; \vec{r}_a, \Omega_a). \quad (2)$$

Although the exact dependence of Eq. (2) on the neutrino flux and the neutrino-nucleon charged current cross section $\sigma_{CC}^{\nu N}$ may be quite complicated, basic physical considerations show that even a rough binning of the events for energy loss and arrival direction may be used to obtain information on both these quantities (see e.g. [14, 15]). In particular, in the following we shall consider the sum of the μ and τ contributions as the experimental observable, namely the energy deposited in the detector and not the energy and/or the nature of the charged lepton crossing the NT. In fact, only for a minor fraction of the detected events the nature of the charged lepton can be reliably established.

According to Ref.s [16, 17], the differential energy loss of the τ leptons per unit of length in an underwater NT can be simply taken as $\mathrm{d}E_\tau/\mathrm{d}\lambda = -\beta_\tau\, E_\tau\, \varrho_w$, with $\beta_\tau = 0.71 \times 10^{-6}$ cm^2 g^{-1} and ϱ_w denoting the water density. Analogously, for muons one just needs to replace β_τ with the corresponding value $\beta_\mu = 0.58 \times 10^{-5}$ cm^2 g^{-1}. Assuming that the lepton energy loss in the NT by e.m. interactions, ΔE_l, is just a small fraction of its energy at the entrance, E_l, we simply obtain $\Delta E_l = \lambda(\vec{r}_a, \Omega_a)\, \beta_l\, E_l\, \varrho_w$, where $\lambda(\vec{r}_a, \Omega_a)$ is the length crossed in the NT by the lepton whose track is defined the geometrical quantities $\vec{r}_a, \Omega_a$.

Using these relations one can derive the spectrum of leptons detected in the NT as a function of their deposited energy, ΔE, and their arrival direction, $\Omega \equiv (\theta, \phi)$, measured in the zenith-azimuth reference frame

$$\frac{\mathrm{d}^2 N}{\mathrm{d}(\Delta E)\mathrm{d}\Omega} = T \sum_{\alpha=\mu,\tau} \sum_a \int \mathrm{d}S_a \int \mathrm{d}E_\nu \, \frac{1}{4\pi}\, \frac{\mathrm{d}\Phi_\nu(E_\nu)}{\mathrm{d}E_\nu}\, \frac{\cos(\theta_a)\; k_a^\alpha}{\lambda(\vec{r}_a, \Omega_a)\beta_\alpha\, \varrho_w}. \quad (3)$$

By denoting with X_i a given bin in energy loss, and with Y_j the one for the zenithal angle, we can integrate the expression (3) to get the number of expected events in $X_i \times Y_j$,

$$N_{ij} = T \sum_{\alpha=\mu,\tau} \sum_a \int_{X_i} \mathrm{d}(\Delta E) \int_{Y_j} \mathrm{d}\Omega \int \mathrm{d}S_a \int \mathrm{d}E_\nu \frac{1}{4\pi}\, \frac{\mathrm{d}\Phi_\nu(E_\nu)}{\mathrm{d}E_\nu}\, \frac{\cos(\theta_a)\; k_a^\alpha}{\lambda(\vec{r}_a, \Omega_a)\beta_\alpha\, \varrho_w}. \quad (4)$$

To take into account the underwater surface profile one can numerically compute the above integral as described in Ref. [8]: by using the available DEM of the area near the NEMO site, one can isotropically generate a large number of oriented tracks which cross the NEMO fiducial volume (see Figure 4 of Ref. [11]) and sample the above integrand. This technique allows also to account for the radial density profile of the Earth (we use the formula reported in [18]).

In order to study the sensitivity to both neutrino flux and $\sigma_{CC}^{\nu N}$ it is necessary to parameterize their standard expressions and the possible departures from them. In particular, we parameterize the flux as $\mathrm{d}\Phi_\nu/\mathrm{d}E_\nu\,\mathrm{d}\Omega_a = C \cdot 1.3 \cdot 10^{-8}\; (E_\nu/\mathrm{GeV})^{-2\,D}$

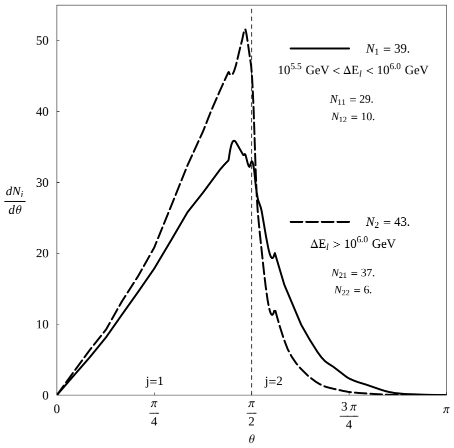

Figure 1: Angular distributions of $(\mu + \tau)$ events collected in five years from a km^3 NT placed at the NEMO site (see text).

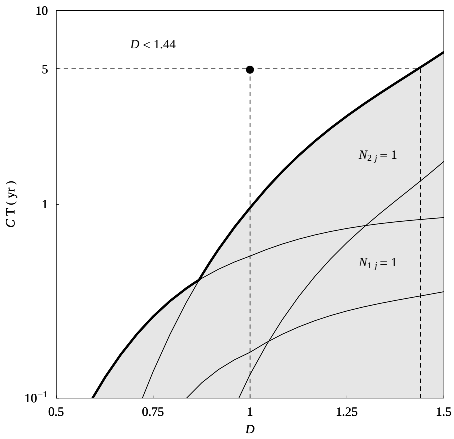

Figure 2: (CT, D) region corresponding to the observation of at least one event in each bin (for standard cross section).

GeV^{-1} cm^{-2} s^{-1} sr^{-1}, which gives a standard Waxman-Bahcall flux [19] for $C = D = 1$. For the neutrino-nucleon cross section we use:

$$\frac{\sigma_{CC}^{\nu N}}{0.344\,\mathrm{nb}} = \begin{cases} \left(\frac{E_\nu}{E_1}\right)^{0.492\,A} & E_\nu \leq E_2 \\ \left(\frac{E_2}{E_1}\right)^{0.492\,A} \left(\frac{E_\nu}{E_2}\right)^{0.492\,B} & E_\nu > E_2 \end{cases}$$

where $E_1 = 10^{5.5}$ GeV is the energy below which the atmospheric flux is expected to dominate (so we consider only the region $E > E_1$) and $E_2 = 10^{6.0}$ GeV. In the low-energy bin this cross-section matches the standard expression [20] for $A = 1$. A value of B significantly larger than 1 may be associated with new physics. Note that the factor C only enters via the product CT as a normalization and can be fixed to $C = 1$, considering instead the exposure time T as the effective variable.

For illustrative purposes, in Figure 1 we report the event angular distribution, for a km^3 NT placed at the NEMO site in five years of operations. The solid and dashed lines correspond to events whose energy loss in the detector belongs to the intervals $10^{5.5}$-10^6 GeV or $> 10^6$ GeV, respectively. The predictions are obtained for standard flux and cross section ($A = B = C = 1$). In the plot are also reported the number of events N_{ij} (see Eq. (4)) when we consider $i = 1, 2$ for the previous two energy bins and $j = 1, 2$ when the zenith arrival direction is between 0° and 90° or 90° and 180°.

Clearly, for a very steep flux power-law index D, the number of events decreases. We shall require that at least one event falls in each bin, in T years of running, in the case of standard cross-section; this rough criterion constrains the parameter range that one experiment is able to explore to the brighter region of Fig. 2, corresponding to the intersection of the regions where $N_{ij} \geq 1$, for all i, j.

As a preliminary result, in Fig. 3 we show the constraints (contours at the 68 % and 95 % CL) which can be obtained on the physical parameters A and D after the marginalization over C is made. Here we are assuming $B = A$, so that the plot represents the capability of the telescope to disentangle the energy dependence of the flux from the energy dependence of the cross-section (in the toy model where both are described by a single parameter). We performed a multi-Poisson likelihood analysis [21], in which the likelihood function, $L = \exp(-\chi^2/2)$, is defined using the following expression for the χ^2 (N_{ij}^0 being the event numbers of the reference model):

$$\chi^2 = 2 \sum_{ij} \left[(N_{ij} - N_{ij}^0) + N_{ij}^0 \ln(N_{ij}^0 / N_{ij}) \right] . \tag{5}$$

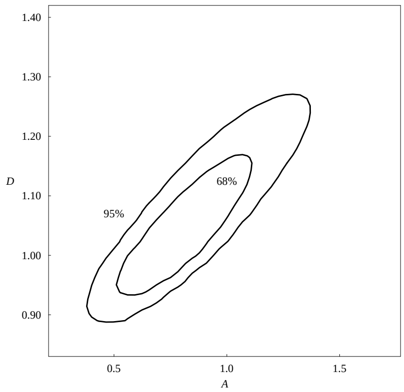

Figure 3: Marginalized contour levels in the (A, D) plane (for $A = B$) (see text for details).

Conclusions

We have performed an analysis of the capability of a km^3 NT in the Mediterranean to disentangle the high energy neutrino flux and neutrino-nucleon cross section in an unexplored kinematical region. Our statistical analysis exploits the dependence of observables on energy and arrival direction (under the hypothesis of an isotropic diffuse flux). Using a simplified toy model to parameterize fluxes and cross-sections, preliminary results confirm that this approach is very promising, and could potentially detect hints of new physics. Of course the real feasibility of such measurements will depend crucially on the size of the neutrino flux which fixes the time required to reach a reasonable statistics. A complete account of this research will be reported in a forthcoming publication.

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