High Energy Neutrinos with a Mediterranean Neutrino Telescope

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Abstract: The high energy neutrino detection by a km\textsuperscript{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\textsuperscript{3} telescope as pursued by the KM3NeT project [7].

Although NT’s were originally thought as $\nu_{\mu}$ detectors, their capability as $\nu_{\tau}$ 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 $\nu_{\mu}$ and $\nu_{\tau}$ 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 $\nu_{\tau}$’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 $\nu_{\tau}$ and $\nu_{\mu}$ detection of a km\textsuperscript{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 $\nu$-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\textsuperscript{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.
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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 $\Sigma_a$ (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 $\Sigma_a$ (see Figure 4 of Ref. [11] for notations). We introduce all relevant quantities with reference to $\nu_\tau$ events, the case of $\nu_\mu$ being completely analogous.

Let $d\Phi_{\nu}/(dE_\nu d\Omega_a)$ be the differential flux of UHE leptons emerging from the Earth surface and entering the NT through $\Sigma_a$ with energy $E_\nu$ is given by

$$\left( \frac{dN_\tau}{dT} \right)_a = \int d\Omega_a \int dS_a \int dE_\nu \frac{d\Phi_{\nu}(E_\nu, \Omega_a)}{dE_\nu d\Omega_a} \int dE_\tau \cos(\theta_a) k_\nu^a(E_\nu, E_\tau; \vec{r}_a, \Omega_a). \quad (1)$$

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

$$N_\tau = T \sum_{a=\mu, \tau} \sum_a \int dS_a \int dE_\nu \int dE_\tau \left( \frac{d\Phi_{\nu}(E_\nu)}{dE_\nu} \right) \cos(\theta_a) k_\nu^a(E_\nu, E_\tau; \vec{r}_a, \Omega_a). \quad (2)$$

Although the exact dependence of Eq. (2) on the neutrino flux and the neutrino-nucleon charged current cross section $\sigma_{CC}^{NN}$ 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 $\mu$ and $\tau$ 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 Refs. [16, 17], the differential energy loss of the $\tau$ leptons per unit of length in an underwater NT can be simply taken as $dE_\tau/d\lambda = -\beta_\tau E_\tau \rho_w$, with $\beta_\tau = 0.71 \times 10^{-6}$ cm$^2$ g$^{-1}$ and $\rho_w$ denoting the water density. Analogously, for muons one just needs to replace $\beta_\tau$ with the corresponding value $\beta_\mu = 0.58 \times 10^{-6}$ cm$^2$ g$^{-1}$. Assuming that the lepton energy loss in the NT by e.m. interactions, $\Delta E_l$, is just a small fraction of its energy at the entrance, $E_l$, we simply obtain $\Delta E_l = \lambda(r_a, \Omega_a) \beta_l E_l \rho_w$, where $\lambda(r_a, \Omega_a)$ is the length crossed in the NT by the lepton whose track is defined the geometrical quantities $r_a, \Omega_a$. Using these relations one can derive the spectrum of leptons detected in the NT as a function of their deposited energy, $\Delta E$, and their arrival direction, $\Omega \equiv (\theta, \phi)$, measured in the zenithal-azimuthal reference frame

$$\frac{d^2N}{d\Delta E d\Omega} = T \sum_{a=\mu, \tau} \sum_a \int dS_a \int dE_\nu \frac{1}{4\pi} \frac{d\Phi_{\nu}(E_\nu)}{dE_\nu} \cos(\theta_a) k_\nu^a \frac{\lambda(r_a, \Omega_a) \beta_a \rho_w}{\lambda(r_a, \Omega_a) \beta_a \rho_w}. \quad (3)$$

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 $X_i \times Y_j$,

$$N_{ij} = T \sum_{a=\mu, \tau} \sum_a \int_{X_i} d(\Delta E) \int_{Y_j} d\Omega \int dS_a \int dE_\nu \frac{1}{4\pi} \frac{d\Phi_{\nu}(E_\nu)}{dE_\nu} \cos(\theta_a) k_\nu^a \frac{\lambda(r_a, \Omega_a) \beta_a \rho_w}{\lambda(r_a, \Omega_a) \beta_a \rho_w}.$$

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 $\sigma_{CC}^{NN}$ it is necessary to parameterize their standard expressions and the possible departures from them. In particular, we parameterize the flux as $d\Phi_{\nu}/dE_\nu d\Omega_a = C \cdot 1.3 \times 10^{-8} \left( E_\nu/\text{GeV} \right)^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, which gives a standard Waxman-Bahcall flux [19] for $C = D = 1$. For
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 $\chi^2$ ($N_{ij}^0$ being the event numbers of the reference model):

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

(5)

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).
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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References


