Ultrahigh Energy Neutrinos With A Mediterranean Neutrino Telescope

E. Borriello\textsuperscript{1,2}, A. Cuoco\textsuperscript{3}, G. Mangano\textsuperscript{1}, G. Miele\textsuperscript{1,2}, S. Pastor\textsuperscript{2}, O. Pisanti\textsuperscript{1}, P. D. Serpico\textsuperscript{4}

\textsuperscript{1}Dipartimento di Scienze Fisiche, Universit\`a di Napoli "Federico II" and INFN Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia, Napoli, 80126, Italy
\textsuperscript{2}Instituto de Física Corpuscular (CSIC-Universitat de València), Ed. Institutos de Investigación, Apdo. 22085, E-46071 Valencia, Spain
\textsuperscript{3}Institut for Fysik og Astronomi, Aarhus Universitet Ny Munkegade, Bygn. 1520 8000 Aarhus Denmark
\textsuperscript{4}Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA

Abstract: A study of the ultra high energy neutrino detection performances of a km\textsuperscript{3} Neutrino Telescope sitting at the three proposed sites for ANTARES, NEMO and NESTOR in the Mediterranean sea is here performed. The detected charged lepton energy spectra, entangled with their arrival directions, provide a unique tool to both determine the neutrino flux and the neutrino-nucleon cross section.

Introduction

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

From the experimental point of view the detection perspectives are stimulated by the several proposals and R&D projects for Neutrino Telescopes (NT’s) in the deep water of the Mediterranean sea, namely ANTARES \cite{ANTARES}, NESTOR \cite{NESTOR} and NEMO \cite{NEMO}, which in the future could lead to the construction of a km\textsuperscript{3} telescope as pursued by the KM3NeT project \cite{KM3NeT}. A further project is IceCube, a cubic-kilometer under-ice neutrino detector \cite{IceCube}, which applies and improves the successful technique of AMANDA to a larger volume.

Although NT’s were originally thought as $\nu_{\mu}$ detectors, their capability as $\nu_{\tau}$ detectors has become a hot topic \cite{Arneodo:2006, Arneodo:2007, Arneodo:2008, Arneodo:2009, Arneodo:2010, Arneodo:2011, Arneodo:2012}, 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, thus requiring for the calculation a careful analysis of the surroundings of the proposed site. The importance of the elevation profile of the Earth surface around the detector was already found of some relevance in Ref. \cite{Auger:2007}, where some of the present authors calculated the aperture of the Pierre Auger Observatory \cite{Auger} for Earth-skimming UHE $\nu_{\tau}$’s, by using the Digital Elevation Map (DEM) \cite{DEM} of the site. In Ref. \cite{Cuoco:2007} the DEM’s of the different areas were used for 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. \cite{Cuoco:2007} in order to apply the detection of UHE $\nu$ as a tool to simultaneously measure the UHE neutrino flux and the $\nu$-N cross section in extreme kinematical regions.

Formalism and results

Following the formalism developed in \cite{Cuoco:2007} we define the km\textsuperscript{3} NT fiducial volume as that bounded
by the six lateral surfaces $\Sigma_a$ (the subindex $a=$D, U, S, N, W, and E labels each surface through its orientation: Down, Up, South, North, West, and East), and indicate with $\Omega_a$ orientation: Down, Up, South, North, West, and East, and indicate with $\Omega_a$ the generic direction of a track entering the surface $\Sigma_a$. We introduce all relevant quantities with reference to $\nu_\tau$ events, the case of $\nu_\mu$ being completely analogous.

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

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

The kernel $k_\tau^a(E_\nu, E_\tau; \vec{r}_a, \Omega_a)$ 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 $E_\tau$. It is the sum of the two mutually exclusive contributions of the events with track intersecting the rock and the ones only crossing water. For an isotropic flux we can rewrite Eq. (1), summing over all surfaces, as

$$\frac{dN_\tau}{dt} = \sum_a \int dE_\nu \int dE_\tau \int d\Omega_a \int dS_a$$

Figure 1: A comparison of the effective apertures $A^{\tau(r,w)}(E_\nu)$ for the three NT sites (see text).

For an isotropic flux we can rewrite Eq. (1), summing over all surfaces, as

$$\frac{dN_\tau}{dt} = \sum_a \int dE_\nu \int dE_\tau \int d\Omega_a \int dS_a$$

The detection performance of a km$^3$ NT placed at one of the three sites in the Mediterranean sea; we plot the ratios $[A^{\tau(r,w)}_{\text{Nestor}} - A^{\tau(r,w)}_{\text{NEMO}}]/A^{\tau(r,w)}_{\text{NEMO}}$ and $[A^{\tau(r,w)}_{\text{Antares}} - A^{\tau(r,w)}_{\text{NEMO}}]/A^{\tau(r,w)}_{\text{NEMO}}$ versus the neutrino energy. The NESTOR site shows the highest values of the $\tau$-aperture for both rock and water, due to its larger depth and the particular matter distribution of the surrounding area, while the lowest rates are obtained for ANTARES.

Figure 2: Angular distributions of $(\mu + \tau)$ events collected in five years from a km$^3$ NT placed at the NEMO site (see text).

$$\left(\frac{1}{4\pi} \frac{d\Phi_\nu(E_\nu)}{dE_\nu}\right) \cos(\theta_\nu) k_\nu^a(E_\nu, E_\tau; \vec{r}_a, \Omega_a).$$  \tag{2}

By using this expression one can also define the total aperture $A^{\tau(r,w)}(E_\nu)$, with “r” and “w” denoting the rock and water kind of events, respectively,

$$\frac{dN^{(r,w)}_{\nu}}{dt} = \int dE_\nu \left(\frac{1}{4\pi} \frac{d\Phi_\nu(E_\nu)}{dE_\nu}\right) A^{\tau(r,w)}(E_\nu),$$  \tag{3}

where

$$A^{\tau(r,w)}(E_\nu) = \sum_a \int dE_\tau \int d\Omega_a \int dS_a \cos(\theta_\tau) k_\tau^{\nu(r,w)}(E_\nu, E_\tau; \vec{r}_a, \Omega_a).$$  \tag{4}

Of course, the same quantities can be defined for muons coming from the charged-current interactions of $\nu_\mu$.
As one can see, the aperture in the three sites can be quite different at high energy but the contribution of this region to the expected number of UHE events per year is suppressed, since one has to convolve the aperture with a neutrino flux which typically drops rapidly with the energy. In Table 1 the event rates are shown assuming a GZK-WB flux [19, 8]. The effect due to the local matter distribution is responsible for the N-S, W-E and NE-SW asymmetries for the ANTARES, NEMO and NESTOR sites, respectively, as expected from the site matter profiles.

Due to the dependence of Eq. (2) on the neutrino flux and the different behavior of the kernels $k_\nu$, one can imagine to use the detected events, properly binned for energy loss and arrival direction, in order to obtain information on both the neutrino flux and the neutrino-nucleon cross section. In particular, one must sum the two lepton contributions in considering the real observable, which is the energy deposited in the detector and not the energy and/or the nature of the charged lepton, either $\mu$ or $\tau$, crossing the NT. In fact, the events whose topology allows for determining the nature of the charged lepton are a negligible fraction of the expected total number.

In order to study the sensitivity to both neutrino flux and $\sigma_{\nu CC}$ it is necessary to parameterize their standard expression and the possible departure from it. In particular, we parameterize the flux as
\[ \phi = 1.3 \cdot 10^{-8} C e^{-2D} \, \text{GeV}^{-1} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} (E_\nu \equiv E_\nu/\text{GeV}), \]
which gives a standard Waxman-Bahcall flux [3] for $C = D = 1$, and allows for a variation of its steepness, via the exponent $D$, and of the normalization, through the multiplicative factor $C$. For the neutrino-nucleon cross section we use:
\[ \frac{\sigma_{\nu CC}^{\nu N}}{10^{-40} \text{cm}^2} = \begin{cases} 0.677 e^{0.492} & e_\nu \in R_1 \\ 5.54 e^{0.363} & e_\nu \in R_2 \\ 5.54 e^{0.363 A f(A, B)} & e_\nu \in R_3 \end{cases} \]
where $f(A, B) = 10^{-0.363(1-A)(7.08+B)}$ and the three regions considered are $R_1 = [2 \cdot 10^4, 1.2 \cdot 10^7]$, $R_2 = [1.2 \cdot 10^7, 1.2 \cdot 10^7+B]$, and $R_3 = [1.2 \cdot 10^7+B, +\infty]$. In particular, $B$ fixes the energy value where new physics appears and $A$ is the change in the energy slope of $\sigma_{\nu CC}^{\nu N}$, and the standard expression [11] is obtained for $A = 1$ and $B = 0$. Note that the factor $C$ can be fixed to its standard value ($C = 1$) since it is just a normalization and thus simply correlated to the exposure time needed to achieve the proper event statistics.

Figure 2 shows how the different flux/cross section configurations can be disentangled by observing the different event angular distributions for a km$^3$ NT placed at the NEMO site in five years of operations. The four curves show the event distribution in two bins of energy deposited in the detector, $10^7$-10$^8$ GeV (LE) or larger than 10$^8$ GeV (HE), while 1 and 2 stay for two possible choices of the parameters: (A=0.8, B=0, D=1) and (A=3, B=1, D=1.02), respectively. Note that the total number of events for the two models are the same.

**Conclusions**

The quite relevant effect shown by Figure 2 supports once more the idea that a km$^3$ NT can provide a real chance to both measure UHE neutrino flux

<table>
<thead>
<tr>
<th>Surf.</th>
<th>ANTARES</th>
<th>NEMO</th>
<th>NESTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0.00590</td>
<td>0.00590</td>
<td>0.00580</td>
</tr>
<tr>
<td>U</td>
<td>0.001677</td>
<td>0.00020/0.2133</td>
<td>0.00020/0.2543</td>
</tr>
<tr>
<td>S</td>
<td>0.01850/0.1602</td>
<td>0.0256/0.1773</td>
<td>0.0240/0.211</td>
</tr>
<tr>
<td>N</td>
<td>0.0241/0.1540</td>
<td>0.0229/0.1823</td>
<td>0.0321/0.1924</td>
</tr>
<tr>
<td>W</td>
<td>0.0212/0.1584</td>
<td>0.0335/0.1691</td>
<td>0.0265/0.2002</td>
</tr>
<tr>
<td>E</td>
<td>0.0206/0.1589</td>
<td>0.0190/0.1875</td>
<td>0.0348/0.1907</td>
</tr>
<tr>
<td>Total</td>
<td>0.0900/0.799</td>
<td>0.107/0.929</td>
<td>0.123/1.039</td>
</tr>
</tbody>
</table>

Table 1: Estimated rate per year of rock/water $\tau$ events at the three km$^3$ NT sites for a GZK-WB flux [19, 8]. The contribution of each detector surface to the total number of events is also reported.
and the neutrino-nucleon cross section in the extreme kinematical region, where some new physics could appear. Of course the real feasibility of such measurements will crucially depend on the size of the neutrino flux which fixes the time required to reach a reasonable statistics. One should keep in mind that these results are derived assuming a Waxman-Bahcall like flux, but one cannot exclude enhanced yields in more exotic scenarios for high energy neutrino production.

Acknowledgements

P.S. acknowledges support by the US Department of Energy and by NASA grant NAG5-10842.

References