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Sensitivity studies for the cubic-kilometre deep-sea neutrino telescope KM3NeT

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Abstract: The observation of high-energy neutrinos from astrophysical sources would substantially improve our knowledge and understanding of the non-thermal processes in these sources, and would in particular pinpoint the accelerators of cosmic rays. The sensitivity of different design options for a future cubic-kilometre scale neutrino telescope in the Mediterranean Sea is investigated for generic point sources and in particular for some of the galactic objects from which TeV gamma emmission has recently been observed by the H.E.S.S. atmospheric Cherenkov telescope. The effect of atmospheric background on the source detection probabilities has been taken into account through full simulation. The estimated event rates are compared to previous results and limits from present neutrino telescopes.

Introduction

The KM3NeT consortium [1] is currently working on a conceptual design for a future Mediterranean neutrino telescope, which will have an instrumented volume of a scale of one km^3.

One of the goals of the KM3NeT Design Study is the optimisation of the detector configuration with respect to the observation of astrophysical neutrino sources. The observation of high-energy neutrino point sources will substantially improve our knowledge and understanding of the non-thermal processes in these sources, and would in particular pinpoint the accelerators of cosmic rays. Good candidates for high-energy neutrino emission are sources of high energy gamma-rays, which have e.g. been observed with the H.E.S.S. atmospheric Cherenkov telescope [2]. In spite of the recent significant progress in the field of high-energy neutrino astronomy, the observation of cosmic neutrinos from such sources is likely to require cubic-kilometre scale neutrino telescopes, such as IceCube [3] and KM3NeT.

In this article two possible configurations of the KM3NeT neutrino telescope are studied to estimate the sensitivity to generic point sources (assuming a neutrino flux proportional to E^{-2}, where E is the neutrino energy), and to selected H.E.S.S. sources (estimating the neutrino fluxes from the observed gamma spectra). The full chain from simulation to reconstruction has been taken into account in this study.

KM3NeT detector configurations

Several detector configurations, including different geometrical layouts and optical sensors, are being considered in the KM3NeT Design Study. The main parameter describing the physics sensitivity of a neutrino telescope is the neutrino effective area. Due to the energy dependence of neutrino interactions and the range of high-energy muons in the detector medium (i.e. sea water), the effective area is a function of the neutrino energy and also of the zenith angle of the direction of observation.

Effective areas for different possible KM3NeT detector configurations have been obtained from a full simulation chain, including: simulation of neutrino-nucleon interactions in the vicinity of the detector (only muon-neutrino charged-current reactions considered); muon propagation and simulation of Cherenkov photons from muons and secondary charged particles; light propagation in the sea water; photon detection by the photo multipliers in the optical modules; reconstruction of the muon tracks from the recorded hits.

In this paper, two different KM3NeT example configurations are presented. The first one is based on already used and well known technology, following the ANTARES design. The second one is a prospective telescope with increased dimensions and a new type of optical modules housing 21 3" PMTs each, distributed over the lower hemispheres of the optical modules [4]. In the following, these configurations are labelled "1" and "2".

Configuration 1 consists of 127 detector strings arranged in a homogeneous hexagon, each with 25 storeys with ANTARES-type optical modules (3×10" PMTs). The distance between lines is 100 m and between storeys 15 m. The simulation was done with the code NESSY, described in [5].

For configuration 2 [6], a geometrical layout with 225 (15×15) strings arranged in a cuboid grid is assumed. The distance between the strings is 95 m, each string having 36 storeys, separated by 16.5 m, with one multi-PMT optical module each.

The neutrino effective areas obtained for both configurations are compared to the ANTARES and IceCube effective areas in figure 1. The effective areas are calculated applying appropriate selection and reconstruction requirements and are given as functions of E. Note that the program chains used to study both configurations are completely independent of each other. As expected, the effective area for configuration 2 is about 2–3 times larger than for configuration 1, as its instrumented volume and total photocathode area are larger. In terms of the latter, both configurations exceed IceCube by factors of about 2 and 3, respectively, which explains the increased effective areas.

The optimal energy interval for the search for neutrino point sources covers 3 decades from 1 TeV to 1 PeV. The event rate $R(\Omega)$ from a neutrino source with celestial coordinates Ω can be calculated as

$$R(\Omega) \approx \int \Phi(E,\Omega) A_\nu(E, \theta(t,\Omega))\, dE\, dt\,, \quad (1)$$

where $\Phi(E,\Omega)$ is a neutrino flux emitted by the source, $A_\nu(E,\theta)$ is the neutrino effective area for the considered telescope configuration and $\theta(t,\Omega)$ is the zenith angle of the source in topocentric coordinates at time t (with a period of one sidereal day). The location of the ANTARES telescope was used to define the local coordinate system.

Neutrinos from point sources

The sensitivity of a neutrino telescope to point sources strongly depends on the energy dependence of the neutrino flux. The current best limit on the neutrino emission from point sources comes from the AMANDA-II neutrino telescope [8] and has been obtained assuming a neutrino flux of the form $\Phi^0_{\nu_\mu} \cdot (E/1\,\mathrm{TeV})^{-2}$. The average limit at 90% C.L. for Northern hemisphere sources, from 1001 days of data (2000–2004), is $\Phi^0_{\nu_\mu} = 5.5 \times 10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The ANTARES neutrino telescope will reach a similar level of sensitivity for Southern hemisphere sources with about 1 year of data taking (assuming a data taking efficiency of 100%). The higher sensitivity of a Mediterranean neutrino telescope to point sources is due to the better angular resolution of the reconstructed muons.

For this study we have calculated expected muon event rates from the point sources in KM3NeT for two different cases: a) for a generic point source with an E^{-2} neutrino flux and b) for selected H.E.S.S. sources. Although all of the more than 30 H.E.S.S. sources will be in the field of view of the KM3NeT neutrino telescope, many of them are expected to be too weak for detection.

The energy distribution of H.E.S.S. sources follows a power law $E^{-\Gamma}$, with a spectral index Γ close to 2. Some sources show the indication of an exponential cut-off in the range of 1–10 PeV. Under certain assumptions, the measured gamma flux can be related to the expected neutrino flux from these sources; for example, in [9] the following assumptions were used:

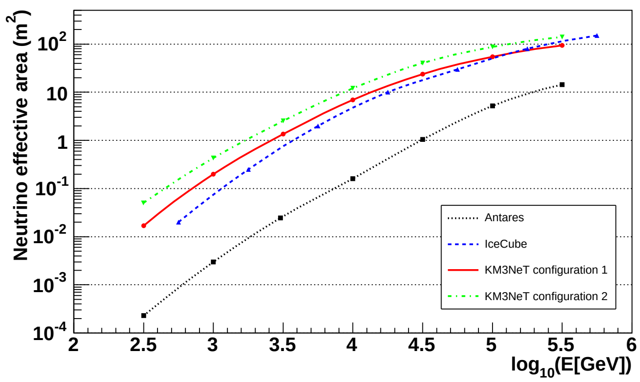

Figure 1: Neutrino effective areas for the considered KM3NeT configurations. The ANTARES and IceCube [7] effective areas are shown for comparison.

- High-energy gamma rays are produced in proton-proton (pp) interactions from hadron (mainly π^0) decays; due to the charge invariance of the strong interaction, π^+, π^- and π^0 are produced in equal abundance and with similar energy spectra. Contributions from $p\gamma$ interactions are neglected.
- There is no significant absorption of γ radiation in the sources, and energy losses of charged particles can be neglected; charged pions decay before interaction.
- Due to the neutrino oscillations the number of muon neutrinos ν_μ (including anti-neutrinos) from the source is equal to the number of gammas produced in π^0 decays.

The neutrino flux derived from the H.E.S.S. measurements can be parametrised in the form

$$\Phi(E) = k_\nu \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\alpha} \exp\left(-\sqrt{\frac{E}{\epsilon}}\right) , \quad (2)$$

where k_ν is the flux normalisation factor, α denotes the spectral index and ϵ the cut-off energy of the source. These parameters were calculated in [10].

Event rates

Event rates from a generic point source as well as for the selected H.E.S.S. sources were calculated according to eq. (1). For generic E^{-2} sources (averaged for sources with declinations between $-40°$ and $-20°$), flux limits as low as $\Phi^0_{\nu_\mu} = 7.7 \times 10^{-12}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ ($\Phi^0_{\nu_\mu} = 2.4 \times 10^{-12}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) could be achieved with 1 year of data from KM3NeT configuration 1 (configuration 2), indicating an increase in sensitivity of a factor of up to 20 in comparison to current AMANDA limits.

The KM3NeT sensitivity to the 3 selected H.E.S.S. sources summarised in table 1 has been evaluated. All these are Galactic sources with an extended emission region, which is larger than the KM3NeT angular resolution (about $0.2°$ above 10 TeV). For these sources the assumptions made above for the neutrino flux calculations are expected to be valid.

The resulting event numbers, assuming an observation time of 5 years, are given in table 2. Calculations were done in the interval 1 TeV – 1 PeV, for the two cases of assuming a cut-off on the neutrino energy spectrum (as indicated in table 1), or not. The left-hand columns (τ_1 and τ_1') correspond to calculations using the effective area including full reconstruction of muon events. Since the muon reconstruction algorithm is not yet fully optimised for the KM3NeT configurations used and by construction suppresses down-going muon tracks, the event numbers were also calculated for a simple selection criterion requiring photon signals from the muon in at least six optical modules; this is an opti-

Table 1: Parameters of selected H.E.S.S. sources. The source diameter (in degrees) is denoted by δ, κ_ν is given in units of 10^{-11} TeV^{-1} cm^{-2} s^{-1} and ϵ in TeV.

			with cut-off			no cut-off	
	Name	$\delta(^\circ)$	κ_ν	α	ϵ	κ_ν	α
1	Vela X	0.80	11.75	0.98	0.84	4.52	2.09
2	RXJ1713.7	1.30	15.52	1.72	1.35	5.65	2.26
3	RXJ0852.0	2.00	16.76	1.78	1.19	6.25	2.29

Table 2: Event numbers from selected H.E.S.S. sources for 5 years of data taking. For each column, the first number (second number in parentheses) indicates the predicted number of events with (without) taking into account the energy cut-off; the numbers after the slash indicate the expected backgrounds from atmospheric neutrinos.

	configuration 2		configuration 1	
	τ_1 / bgr	τ_2 / bgr	τ_1' / bgr	τ_2' / bgr
1	10.0 (16.0) / 13.0	23.6 (34.8) / 34.0	2.1 (2.9) / 1.9	5.0 (6.9) / 4.2
2	6.4 (11.2) / 23.3	15.8 (25.2) / 61.0	1.4 (2.2) / 8.1	3.4 (5.1) / 17.3
3	6.4 (12.9) / 59.0	15.8 (29.2) / 154.5	1.4 (2.5) / 19.6	3.5 (6.1) / 43.3

mistic but reasonable estimate. The resulting event numbers are shown in the right-hand columns (τ_2 and τ_2'). The background of atmospheric neutrino event numbers calculated using the Bartol parameterisation [11] is also given.

Conclusions

Sensitivity to point sources of the future Mediterranean KM3NeT neutrino telescope have been considered for two different configurations. Neutrino effective areas for these configurations have been obtained using a full simulation and reconstruction chain. In the considered energy interval (about 0.1–100 TeV) the effective areas of both configurations are larger than the IceCube effective area. The study indicates that the KM3NeT telescope can significantly improve the current limits on generic point sources. The expected number of events from given sources rises with the instrumented volume and the total photocathode area assumed. With the larger of the two KM3NeT configurations studied, the brightest H.E.S.S. sources would be detectable within less than a decade. However, one has to note that for these studies the atmospheric muon background was neglected, and the energy reconstruction has been treated as perfect.

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