KM3NeT: study of the angular acceptance for a high energy neutrino telescope in the Mediterranean Sea

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Abstract

Simulations for the study of the angular acceptance for a high energy neutrino telescope in the Mediterranean Sea are performed in the frame of the KM3NeT Design Study. In particular we have investigated how the PMT orientation can affect the performance of a km3 detector based on towers with a pair of optical modules equipped with 10" PMTs at each edge of the storey. Some preliminary results for three different PMT orientations are presented and the expected effect on the detection of point-sources and a diffuse flux of very energetic neutrinos is discussed. Moreover, a first attempt to study the response to atmospheric muons for different PMT orientations was also undertaken aiming both at the rejection of the atmospheric muons mis-reconstructed as up-going and the detection of the Moon shadow. However, due to the large detector volume, a huge statistics is needed to achieve an adequate livetime. For this reason we started a mass production of atmospheric muons at several detector depths.

Key words: Neutrino telescope, neutrino effective area, atmospheric muon background.
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1. Introduction

The KM3NeT Design Study[1], which is funded by the EU in the frame of the 6^{th} Framework Programme, aims at the definition of a complete project for an underwater km^3 neutrino telescope to be installed in the Mediterranean Sea. The major scientific goal is the study of the non-thermal Universe via high energy astrophysical neutrinos. Many interesting potential sources of neutrinos are expected over an energy range that spans many orders of magnitude: from hundreds of GeV to the GZK energies. However, due to the very small number of events expected, a single detector cannot cover with high efficiency the whole energy range. In the KM3NeT Design Study the telescope detection efficiency is optimized for muon neutrinos in the energy range 1 TeV $\leq$ E $\leq$ 1 PeV which is the most promising energy range for point-source search of both galactic and extra-galactic neutrino sources. In this energy range neutrino signals, due to the huge presence of the down-going atmospheric muon background, have to be searched for mainly in up-going neutrinos. Moreover due to the peculiar nature of neutrinos, the Universe is basically transparent to them, therefore high energy neutrinos can reach our detector even from the most remote regions of the cosmos thus building up an unresolved diffuse flux that should overwhelm the muon and neutrino atmospheric background at energy above about 100 TeV. However, since with increasing energies above a few tens of TeV the effect of Earth opacity becomes

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more and more important thus reducing the neutrino detection efficiency for up-going neutrinos, at high energy the most important contribution to the neutrino detection comes from the angular region around and above the horizon. A rather wide angular acceptance is needed for the underwater km^3 neutrino telescope in order to maximize the detection efficiency for up-going neutrinos (1 TeV $\leq$ E $\leq$ 100 TeV) and for very energetic neutrinos ($\geq$ 100 TeV) around and above the horizon. Another important goal is to reduce the number of atmospheric muons mis-reconstructed as up-going. Moreover, the detection of a deficit in the muon flux corresponding to the position of the Moon, the so-called moon shadow effect, can provide an important tool for the absolute pointing of the telescope as well as for an estimate of its angular resolution.

2. Simulations

In this contribution we report some preliminary results on simulations performed with a MonteCarlo code[2],[3] developed in the ANTARES collaboration and then adapted to be used for km^3 detector geometries[4]. In the Conceptual Design Report of KM3NeT[7] a few possible solutions are presented for both the Detection Unit that is the basic modular structure of the detector and for the Optical Modules that host the photo-detection sensors. Two different Detection Unit concepts are considered, namely the string that is a uni-dimensional structure and the tower that is a three-dimensional structure, while the Optical Modules can be equipped with one large PMT (10" diameter or more) or many smaller photo-sensors. In the following we will show the performance of a km^3 neutrino telescope made of 169 towers arranged in a 13x13 square lattice with inter-tower distance of 140 m. Each tower consists of 18 rigid bars, 20 m length, equipped with a pair of optical modules (with 10" PMTs) at each edge of the bar. Bars are spaced by 40 m and each bar is orthogonal to the adiacent one. The main input parameters of the simulations are:

- E^{-2} neutrino spectrum
- site properties of the Capo Passero site (3500 m in depth, absorption length of 67 m at $\lambda \sim 440$ nm, 40 kHz of optical background,...)
- hit trigger selection based on hit coincidence in a pair of PMTs at the edges of the bars within 20 nsec OR hit on a single PMT with amplitude higher than 2.5 p.e.
- reconstruction algorithm based on a maximum likelihood estimator[5]
- 23% quantum efficiency at 390 nm.

The spectral dependance of the photocathode quantum efficiency is the one reported in the Hamamatsu catalogue for the R7081 10" PMT, however it is worth mentioning that several companies are developing large PMTs with quantum efficiency as high as 45% that could represent a major improvements in high neutrino detection as described in ref [6]. In fig. 1 effective neutrino detection areas for reconstructed muon neutrino events are reported as a function of neutrino energy for several bins of neutrino angle of incidence. The effect of the Earth absorption shows up at about 100 TeV and increases with increasing energy. At the highest simulated energy almost only neutrinos around and above the horizon can be detected. In this simulation each pair of Optical Modules at the edges of the bar has one PMT down-looking and the other one horizontal-looking.

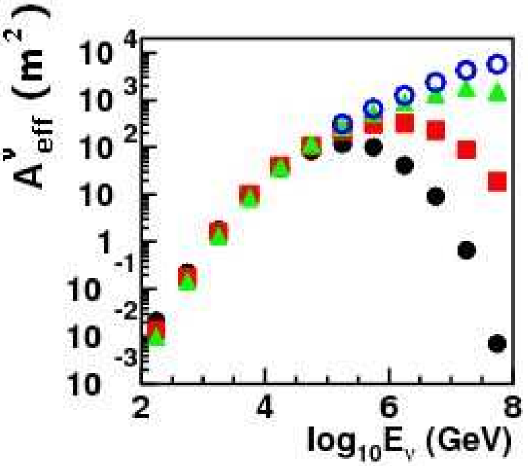

Fig. 1. Effective neutrino detection areas as a function of energy for different neutrino angle of incidence. Full circles 0° $\leq \theta \leq$ 30°, squares 30° $\leq \theta \leq$ 60°, triangles 60° $\leq \theta \leq$ 90° and open circles 90° $\leq \theta \leq$ 120°

In this contribution we would like to address the issue of the angular acceptance for an underwater km^3 neutrino telescope as a function of PMT orientation. Indeed the PMT orientation is expected to affect detector performance in several different respects. We have investigated three different configurations of the PMTs at the edge of the bar with different angular acceptances: down-horizontal (dh), down-looking at 45° (dd), and up-down (ud).

The response of the different PMT orientations in the energy region above one TeV that is the most promising for point source search is shown in fig. 2. Effective areas are reported versus the cosine of the incident neutrino angle for up-going neutrinos ($0^\circ \leq \theta \leq 90^\circ$) in the bottom part of fig. 2. The dd and dh configurations show a similar trend with an overall effective area slightly higher for the dd configuration, while the ud configuration exhibits smaller effective areas especially for the horizontal events.

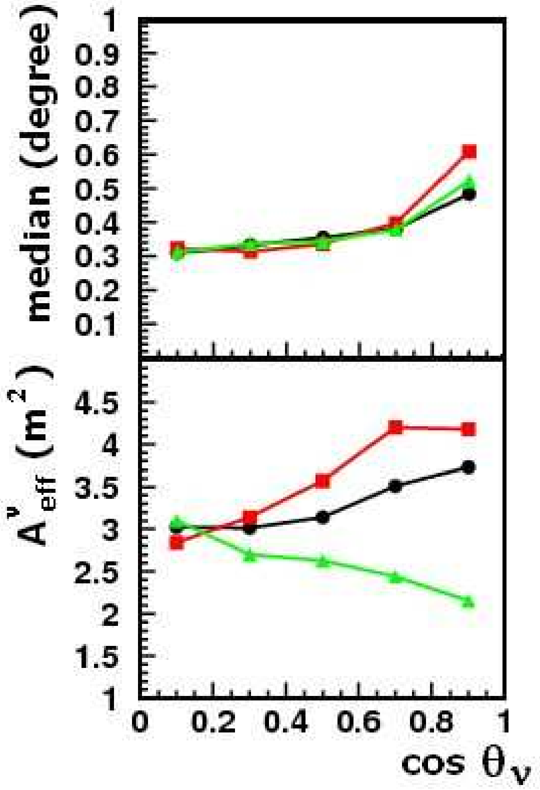

Fig. 2. Median of the angle between the true and the reconstructed muon direction (top) and effective neutrino areas (bottom) for neutrinos in the energy range 1 TeV $\leq$ E $\leq$ 100 TeV. Cuts on the likelihood were applied in order to get an angular resolution of about 0.1° at 30 TeV for all orientations. Squares: dd orientation, circles: dh orientation and triangles: ud orientation.

In fig. 3 the angular resolutions and the effective areas for neutrino energy higher than 100 TeV are reported for the three different configurations. The trend of the effective areas as a function of the incident neutrino direction reported in the bottom of fig. 3 reflects the convolution between the geometrical area and the neutrino interaction probability. However, no significant difference is observed for the three different orientations. A minor difference is observed in the angular resolution (top of fig. 3) for down-going events closer to the vertical direction where the dh and especially the dd configurations exhibit a slightly worse median angle between the true and reconstructed muon direction.

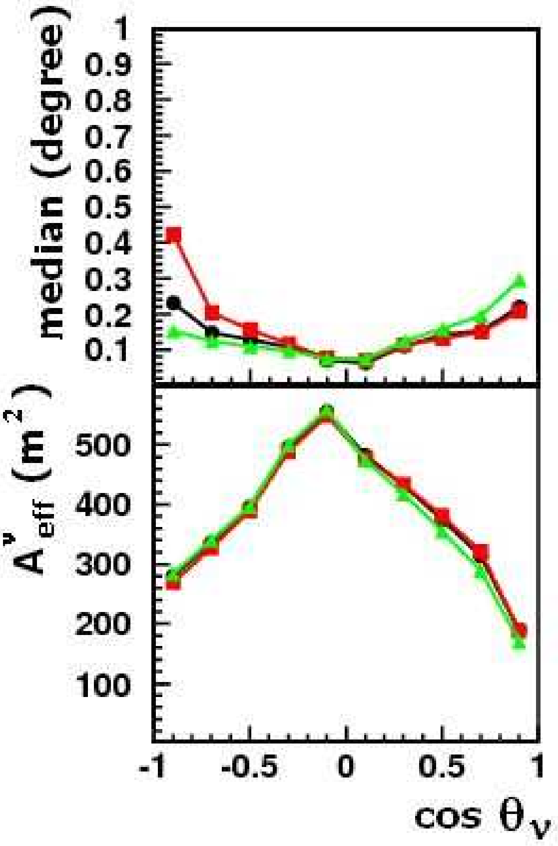

Fig. 3. Median of the angle between the true and the reconstructed muon direction (top) and effective neutrino areas (bottom) for neutrinos in the energy range 100 TeV $\leq$ E $\leq$ 100 PeV. Squares: dd orientation, circles: dh orientation and triangles: ud orientation.

Another important issue is the rejection of atmospheric muons which represent an important source of background for high energy neutrino telescopes. Indeed, although the telescopes are installed below several thousand meters under-water or under-ice, the down-going flux of muons at the detector depth exceeds the atmospheric neutrino flux by about 5-6 orders of magnitude. Therefore, the small fraction of muons that are mis-reconstructed as up-going muons appear as fake neutrino signals. The effect of mis-reconstructed atmospheric muons on detector performance is expected to depend both on depth and on the reconstruction algorithm. A complete study of the atmospheric muon background has to be done with massive event production that requires huge CPU time in order to simulate live-times comparable to the observation time needed for cosmic neutrinos. In the following we report some preliminary results concerning atmospheric muon reconstruction and rejection for different PMT orientations. Atmospheric muons are simulated with the code MUPAGE [8] that provides a parametrization of the muon flux, including multi-muons, at the detector depth.

orientation	tot. rec.	up-going	after cut
ud	1777497	99945	398
dd	899142	76843	219
dh	1187059	69218	100

Table 1
Number of reconstructed atmospheric muon events for a live-time of about 105 min for different PMT orientation. First column: all reconstructed events; second column: events reconstructed as up-going, third column: events reconstructed as up-going after quality cuts as in fig. 2

Atmospheric muon events are then propagated through the detector volume and eventually reconstructed by means of the ANTARES code. Some preliminary figures concerning the response to atmospheric muons for different PMT orientations are reported in table I.

3. Conclusions

In this work we have investigated the effect of the angular acceptance of the Optical Modules on the performance of a km^3 underwater neutrino telescope. At neutrino energies 1 TeV $\leq$ E $\leq$ 100 TeV where detector performance will be optimized the up-down arrangement of the PMTs is less efficient than the down-down and down-horizontal ones. At high energy, greater than 100 TeV, no significant differences are observed for the three different configurations. A preliminary study of the muon atmospheric background and its impact on detector performance for the three different PMT orientations considered in this work shows that the down-horizontal configuration has a lower number of atmospheric muons mis-reconstructed as up-going. An estimate of the observation time required to detect a muon flux deficit due to the Moon shadow for the three different PMT orientations is in progress. A complete atmospheric muon study requires adequate statistics in order to be plugged into a complete sensitivity study for both point-sources and diffuse fluxes that includes both atmospheric muon and neutrino backgrounds. Different detector depths should also be simulated.

Acknowledgement

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