KM3NeT: optimization studies for a cubic kilometer neutrino detector

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Abstract

In the KM3NeT collaboration an important task is the simulation of the detector performance which aims at the optimization of the detector design. In this work the effect of two important items are studied: the PMT photocathode quantum efficiency and the effect of the bar length of a three dimensional detection units. Simulation studies including the improved PMT photocathode quantum efficiency show that, especially at energy below 100 TeV, the increasing of the neutrino effective area is important. Moreover, simulations that optimize the geometry of one of the detection units proposed in KM3NeT are presented. In particular an increase in the effective areas for longer bars is observed.

Key words: neutrino, telescope, simulation
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1. Introduction

KM3NeT [1] is a consortium including many institutions from nine different countries. Activities are funded by the EU with the final aim to conceive a Technical Design for a cubic kilometer neutrino telescope to be installed in the Mediterranean sea. The main physics goal of the telescope is the observation of the weak fluxes of high energy neutrinos from sites of acceleration of high energy particles in the Universe. Its location permits the observation of the center of our Galaxy and of the largest part of the southern sky ensuring full complementary with the under-ice IceCube telescope [2], that is under construction at the South Pole.

The telescope consists of a cubic kilometer volume instrumented with a large number of photo sensors which is able to detect neutrinos and trace back their direction. The neutrino detection principle is based on the detection of the Cherenkov light emitted by secondary particles created in the neutrino interactions and propagating in the optically transparent sea water.

The collaboration is exploring the most advanced technologies in the fields of light detection units, electronics, data transmission, mechanical structures, power supply etc.

The basic detector components are the photo sensors that detect the Cherenkov light. These are arranged on vertical structures called detection units.

The sensitivity of the telescope to high energy neutrino fluxes depends on the pointing resolution of the detector and effective area. MonteCarlo simulations studying the performance of the detector in terms of angular resolution and effective areas, can provide indications to optimize the geometrical arrangement of the photo-sensors. The simulated detector configuration should fulfill technical and cost requirements. In this work we will address two issues: the effect of the improved PMT Quantum Efficiency (QE) and the effect of the PMT position

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on the detection units. In particular the influence of having a horizontal spacing of photo sensors on the same storey. The effects of the PMT orientation are discussed in [3].

MonteCarlo simulations, including the detector geometry, the neutrino interaction, the light generation, the propagation in water up to the detector and the detector response, have been carried out using the ANTARES codes [4],[5] modified for a km^3 detector [6]. A track reconstruction algorithm, developed in the ANTARES collaboration and adapted to this geometry, was implemented in order to evaluate the muon, and consequently the neutrino direction.

2. PMT Quantum Efficiency effect

Recently, several photomultiplier manufacturers have developed new bi-alkali photocathodes with improved photocathode QE. To evaluate the effect on the detector performance we simulated a E^{-2} up-going neutrino spectrum in the energy range from 10^2 GeV to 10^7 GeV. The simulated geometry consists of 169 (square array of 13×13 structures) NEMO towers with an horizontal spacing of 140m. The simulated NEMO tower consists of a sequence of 18 rigid bars, 20m length, having on each end 2 PMTs one down looking and the other horizontally looking. The bars placed at vertical a distance of 40m are orthogonal one with respect to the near one. The instrumented detector volume is ∼1.9 km^3. The main inputs to the simulation are:

- Capo Passero water optical parameters [7]
- 40 kHz uncorrelated optical background uniformly distributed in a ± 1 μsec window around the event
- event selection based on triple coincidence between PMTs in the bar (3/4) in logic OR with the presence of high charge hits ($\geqslant$ 2.5 p.e.)
- reconstruction algorithm based on maximum likelihood estimator [8]

The full spectral dependence of the photocathode QE was implemented in the simulation. The standard (max value 23% at 390 nm) [1] , super (max value 35% at 380nm) and ultra (max value 43% at 390nm) bi-alkali [2] were compared.

Neutrino effective areas as function of the neutrino energy are reported in Fig. 1 (top panel) for the three cases. For super and ultra bi-alkali the rate of optical background was increased according to the increased QE. The neutrino effective areas are obtained imposing cuts on the reconstruction quality in order to get an angular resolution of around 0.15° (angle between the simulated induced muon and reconstructed directions) at 30 TeV. This angular resolution is similar to the angular resolution obtained, for this detector configuration, from sensitivity for point like sources studies. For comparison in Fig. 1 the "reference effective area" reported in the Conceptual Design Report (CDR) of the KM3NeT collaboration [10] is shown (black line). This "reference neutrino effective area" is obtained with a reference detector that is not the KM3NeT final detector configuration and consists of 225 detection units (square array of 15×15) each equipped with 37 OM hosting 21 3" PMTs with a maximal QE value of 33% at 390nm all down-looking (in total 174825 PMTs). The distance between detection units is set to 95m and the vertical distance between storeys to 15.5m. The instrumented detector volume is ∼1 km^3.

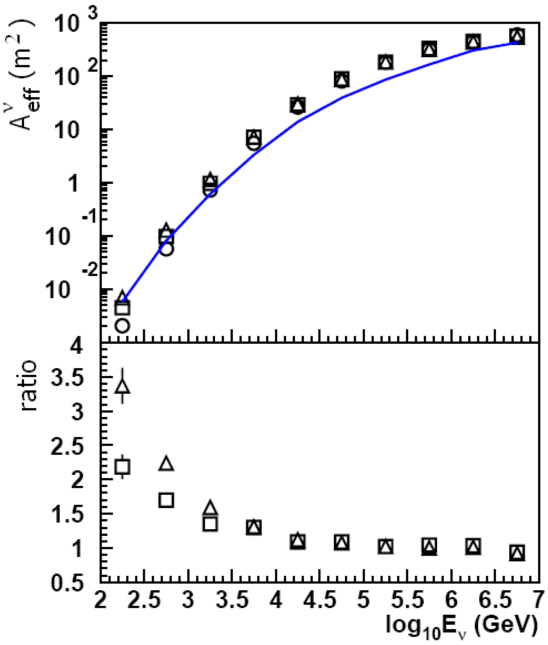

Fig. 1. Top panel - Neutrino effective areas as a function of the neutrino energy for the same detector equipped with PMTs with different photocathode QE. Circles are for standard PMT QE, squares for super bi-alkali and triangles for ultra bi-alkali photocathode. For comparison the "reference effective neutrino areas" is also reported (line) (see text). Bottom panel - Ratio between the super bi-alkali (square) and ultra bi-alkali (triangles) with respect to the standard PMT QE effective area.

[1] QE reported in the Hamamatsu catalog for the 10" PMT R7081

[2] super and ultra QE reported in the Hamamatsu catalog [9]

As expected, the effects of the improved photocathode QE is relevant at lower energy where the number of photons per track length unit is smaller. At 1 TeV the neutrino effective area increases by a factor ∼1.5 for the super and ∼1.8 for the ultra QE PMTs for the studied detector configuration. Moreover, for QE comparable or higher to the one of reference detector, detectors made of 169 towers exhibits similar performance for energies lower than 1 TeV and better performance for higher energies.

3. Storey size effect in the detection unit

One more important item for the design of a km^3 the detector are the detection units. The large number of detection units expected for a cubic kilometer detector requires an easy and safe deployment, assembling and connection procedures. The design of a detection units is a compromise between the detector performance, cost and technical requirements.

Two conceptual different designs for the detection units have been proposed in the KM3NeT collaboration: the string structure and the tower structure [10].

The string is a one-dimensional structure which consists of a sequence of very compact storeys which hosts one or few Optical Modules (OM). Both ANTARES [11] and IceCube [2] collaborations deployed string structures in deep sea and in ice respectively and are now taking data. ANTARES has completed its detector with 12 strings. Each string has 25 storeys each one hosting 3 OMs. IceCube presently has 40 strings deployed with 60 OMs per string and 1 OM per storey.

The tower is a three-dimensional structure which consists of large rigid storeys which can support several OMs. In the KM3NeT CDR [10] two three-dimensional structures have been proposed: a NEMO like and a NESTOR like detection unit. In this work an optimization study on NEMO like detection units will be shown.

The NEMO [12] collaboration has developed a structure that can be transported and deployed in a compact configuration and unfurled on the sea bed. One of such structure was tested in deep sea near the Sicilian coasts [13].

In this work the muon effective area and angular resolution will be explored for a km^3 detector of NEMO like detection units. In particular, in order to optimize the bar length for NEMO tower structures, simulations have been performed as a function of the bar length going from very short bars (1m, a string like structure) to long bars (20m, a three-dimensional structure).

Up-going muons with energies from 10^2 GeV to 10^6 GeV with a flat spectrum have been generated and the angular resolution and effective area calculated. In this case a smaller detector was simulated (square array of 8x8 NEMO towers) equipped with PMTs with standard values of photocathode QE.

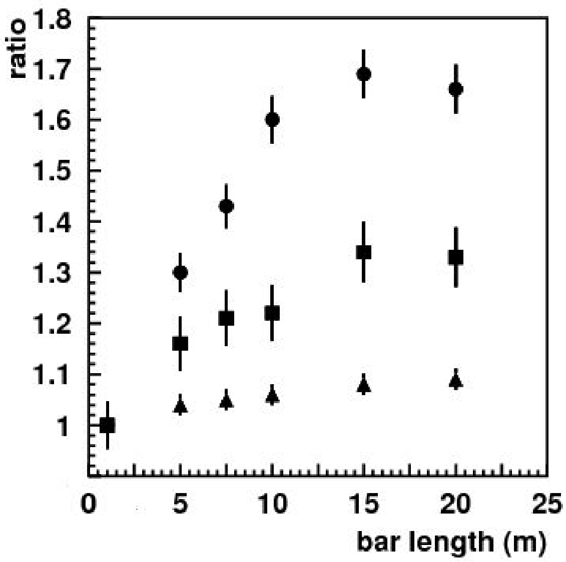

Fig. 2. Ratio of effective areas with respect to the 1m bar length structure is reported as function of the bar length for different energy ranges: 100 GeV ÷ 1 TeV full circles, 1 TeV ÷ 10 TeV full squares and 10 TeV ÷ 1 PeV full triangles.

In Fig. 2 ratios of the muon effective areas with respect to the effective areas of the 1m bar length structure are reported as a function of the bar length for different energy ranges. In order to have a fair comparison, quality cuts were applied in order to get similar angular resolutions (of about 0.12° at 30 TeV in the median of the angle between the generated and reconstructed muons). The effective area increases with increasing bar length and saturates between 10m and 15m. An analysis of the angular resolution as a function of the zenith angle shows that the increase of the effective area is mainly due to better reconstruction of vertical muon tracks. This effects has been already shown in [14] where effective areas and angular resolution for a detector equipped with three-dimensional NEMO towers (20 m bar length) have been compared with a detector equipped with uni-dimensional structures.

4. Conclusions

In this work the effect on the km^3 detector performance of the PMT photocathode QE and the effect of the size of the storey have been explored in terms of effective area and angular resolution in the case of a detector with NEMO like detection units.

Since the energy spectra of the most relevant neutrino sources are expected to decrease with increasing neutrino energy, the energy range of main interest for a km^3 detector has been identified in the range between 1 TeV and 1 PeV [10]. Our simulations show that the effect of the improved QE in this energy range is relevant in particular in the lower region of the energy range (< 10 TeV). The use of high QE PMTs in KM3NeT may be considered taking into account that small photocathode area PMTs are already available on the market and prototypes of large area PMTs have been developed. Moreover, their use doesn't imply changes in the detector design.

The second item explored in this work is the effect on the detector performance of bar length in a NEMO like detection unit. The simulation results show that among the studied geometries the detector with a three-dimensional detection unit has better performance with respect to a detector with a string like structure and indicate that the optimal bar length is around 10m and 15m.

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