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The ANTARES neutrino telescope

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Abstract. The ANTARES detector is the largest underwater neutrino telescope. It is installed in the Mediterranean Sea, at a depth of about 2500 m, close to Toulon, France. The Cherenkov photons emitted along the path of neutrino induced muons are detected by a 3-dimensional array of photomultipliers and used to reconstruct their trajectory. The construction of the detector was completed in May 2008. A short description of the experimental setup is given and some selected results are presented.

1 Introduction

The ANTARES neutrino telescope is a three-dimensional array of 885 photomultipliers (PMTs) distributed over 12 mooring lines installed in the Mediterranean Sea, 40 km off the French coast at 42°50'N, 6°10'E. Thanks to its location in the Northern hemisphere, the Galactic Centre is included in its field of view. This makes ANTARES complementary to the South Pole telescopes, Amanda and IceCube, (Abbasi et al., 2009). The main goal of the experiment is the search for high energy neutrinos from astrophysical sources such as Active Galactic Nuclei, μ-quasars, supernova remnants, gamma-ray bursters and from unresolved sources (diffuse neutrino flux). Neutrinos represent an excellent probe to explore remote astrophysical objects, as they interact weakly with matter, are able to cross very large distances, inaccessible to protons and gamma rays, and are not deviated by magnetic fields, pointing back to their sources. An overview of neutrino astronomy is presented in this conference, (Kouchner, 2011). The telescope is optimized for the detection of muon neutrinos, since muons resulting from charged current interactions can travel kilometers and are almost collinear with the parent neutrinos at energies above 1 TeV. The detection principle is based on the collection of the Cherenkov light emitted along the trajectory of high-energy charged particles produced in neutrino interactions; using dedicated algorithms the trajectory of the Cherenkov light emitting particles can be reconstructed.

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2 Experimental setup

The ANTARES detector, schematically shown in Fig. 1, consists of 12 flexible lines, each with a total height of 450 m, separated by distances of 60–70 m from each other. They are anchored to the seabed and kept near vertical by buoys at the top of the line. Each line, apart line 12, carries a total of 75 optical modules (OM), 10" Hamamatsu PMTs housed in glass spheres, arranged in 25 storeys (3 optical modules per storey) separated by 14.5 m, starting 100 m above the seafloor. Line 12 carries only 60 OMs in order to host the acoustic system AMADEUS, see below. Each PMT is oriented 45°downward with respect to the vertical. A titanium cylinder in each storey houses the electronics for readout and control, together with compasses and tiltmeters used to measure the heading and the inclination of the storeys. A system of acoustic transponders and receivers distributed over the lines and on the seabed allows the measurements of the OM positions with an accuracy of about 10 cm. A system of LED beacons housed in some of the storeys and laser beacons located at the bottom of two of the lines are used for timing calibration. The PMT signals are digitized by a custom built ASIC chip, (Aguilar et al., 2010a). For analog pulses which are larger than a preset threshold, typically 1/3 photoelectron, the arrival time and the integrated charge of the pulse are measured and the digitized data are sent to shore. The data stream is processed by a computer farm at the shore station which searches for different physics signals according to

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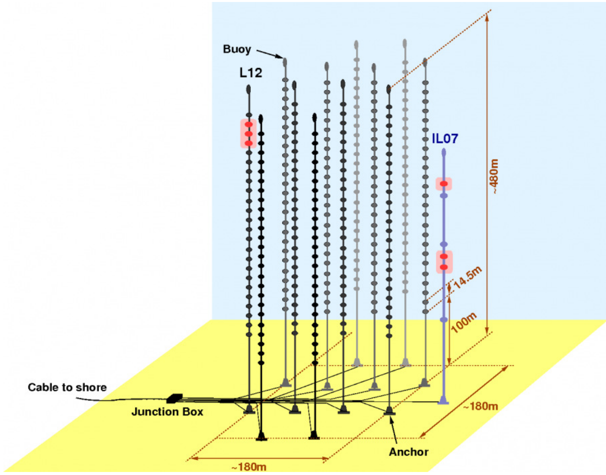

Fig. 1. Schematic view of the ANTARES detector.

predefined trigger conditions.The DAQ system is described in detail in (Aguilar et al., 2007).

3 Selected results

A large number of events have been collected during 2007 (using 5 lines) and 2008 – 2010 (10 and then 12 lines). Detailed comparisons have been made with Monte Carlo expectations. Some selected results are shortly presented hereafter.

3.1 Depth intensity relation of atmospheric muon flux

Atmospheric muons are produced mainly in the decay of charged mesons (π, K) resulting from the interaction of high energy cosmic rays with atomic nuclei in the atmosphere. They can have enough energy to reach the ANTARES depth. In this case they represent a background for neutrino detection, but they can also be useful to verify the detector response. Data collected in 2007 with 5 lines were used to determine the depth-intensity relation of atmospheric muons, i.e. the vertical muon flux versus depth, h, (Aguilar et al., 2010b). Given the muon intensity, $I(\theta, h_o)$, at a certain depth h_o as a function of direction, the vertical intensity of the muon flux as a function of depth underwater $I(\theta=0, h)$ is calculated, using the relation:

$$I(\theta=0,h) = I(\theta,h_o)\cdot|\cos(\theta)|\cdot c_{\mathrm{corr}}(\theta)$$

where $h = h_o/\cos(\theta)$ is the effective slant depth and $c_{\mathrm{corr}}(\theta)$ is a geometrical correction factor which takes into account the curvature of the Earth, (Lipari, 1993; Gaisser, 1990). The results are shown in Fig. 2, together with a collection of measurements from other experiments and with an analytical parameterization (see figure caption for references). Statistical errors are small and not visible. The error band represents the systematic errors due to the uncertainties on parameters which describe the detector and the water properties.

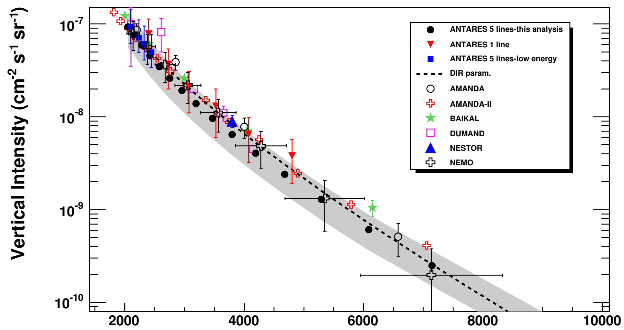

Fig. 2. Vertical muon flux of atmospheric muons for the 5 line ANTARES data (black points) as a function of the slant depth. Downward triangles show the results from line 1 data, (Ageron et al., 2009). Full squares show the results obtained with a new method and a low muon energy event selection, (Aguilar et al., 2010c). Expectation from Bugaev parametrization (dotted line) is superimposed, (Bugaev et al., 1998). A compilation of results obtained with other underwater detectors is shown: AMANDA, (Andres et al., 2000), AMANDAII, (Desiati et al., 2003), Baikal, (Belolaptikov et al., 1997), DUMAND, (Babson et al., 1990), NESTOR, (Aggouras et al., 2005), NEMO, (Aiello et al., 2010).

3.2 Atmospheric neutrinos

A preliminary analysis of the full detector data was made to reconstruct the angular distribution of the events. A total of 1062 neutrino candidate events were found in 341 days of detector live time. Figure 3 shows the comparison with Monte Carlo expectations of the elevation angle of the track. Atmospheric muon events were simulated using the CORSIKA shower simulation program, (Heck, 1998), with the QGSJET hadronic interaction model, (Kalmykov and Ostapchenko, 1993). A model described in Bugaev et al. (1998) has been chosen for the chemical composition of primary cosmic rays. It is worth recalling that atmospheric muon events $(0 < sin(\theta) < 1)$ can be due to the simultaneous arrival of several muons (multiple muon events), but only one track is reconstructed with the present reconstruction algorithms. The band around Monte Carlo represents the systematic uncertainties due to the error on detector and environmental parameters. For neutrino simulation, the Bartol parameterization was used for the atmospheric flux, (Barr et al., 2004). The effect of neutrino oscillations is included. In this analysis a fast reconstruction algorithm, (Aguilar et al., 2011a), was used, whose estimated resolution for angle is around 1°.

3.3 Search for pointlike sources

A search for cosmic sources of high energy neutrinos has been performed using data collected during 2007 and 2008, for a total livetime of 295 days. A better angular resolution is required for this analysis than for the atmospheric neutrino study. A more precise reconstruction strategy was used,

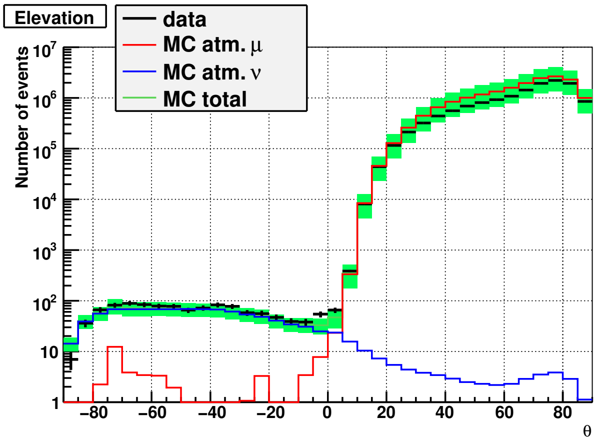

Fig. 3. Angular distribution of the reconstructed ANTARES events.

whose space angle resolution is estimated to be 0.5±0.1 degrees. A list of 25 sources in the visible sky of ANTARES has been considered to search for clusters of events. Including systematic uncertainties, the neutrino flux sensitivity is around $7.5 \cdot 10^{-8}\, E^{-2}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}$, (Kouchner, 2011). Figure 4 shows the sky map of the events in galactic coordinates. No statistically significant excess has been found.

3.4 Search for neutrinos from diffuse flux

Data collected between December 2007 and December 2009 were used to search for a diffuse flux of astrophysical muon neutrinos. A $(0.83\times\, 2\pi)$ sr sky was monitored for a total of 334 days of equivalent live time. The searched signal corresponds to an excess of events, produced by astrophysical sources, above the expected atmospheric neutrino background, without any particular assumption on the source direction. A robust energy estimator, based on the mean number of hits on the same OM produced by direct and delayed photons in the detected muon-neutrino events, was used to select high energy neutrino candidates. No significant excess was found and a 90% c.l. upper limit on the diffuse flux with a E^{-2} spectrum is set at $5.3 \cdot 10^{-8}\, E^{-2}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in the energy range 20 TeV to 2.5 PeV. Figure 5 shows the ANTARES limit together with the results from other experiments, (Aguilar et al., 2011b).

4 Acoustic detection

ANTARES contains an acoustic detector system called AMADEUS (ANTARES Modules for the Acoustic Detection Under the Sea, Aguilar et al., 2011c). The system extends the ANTARES detector by a dedicated array of custom designed acoustic sensors for the broad-band recording of signals with frequencies ranging up to 125 kHz. The project was conceived as a feasibility study for a potential future

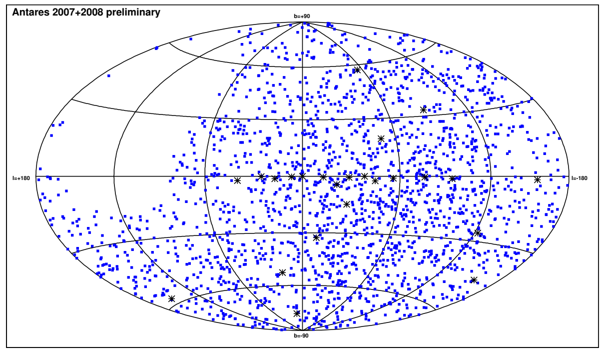

Fig. 4. Sky map of ANTARES neutrino events in galactic coordinates.

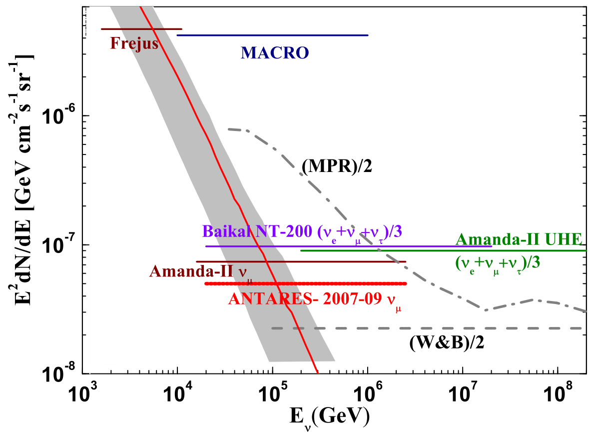

Fig. 5. ANTARES upper limit for a E^{-2}diffuse high energy neutrino flux, compared with the results from other experiments.

large-scale acoustic detector for extremely high energy neutrinos from the cosmos. The AMADEUS design combines local clusters of acoustic sensors with large cluster spacing. Within each acoustic cluster, suppression of random noise by requiring local coincidences and reconstruction of the arrival direction of an acoustic wave are possible. From the direction reconstruction the position of a source can be inferred, Fig. 6.

5 Earth and Sea science

ANTARES is also a multidisciplinary undersea observatory. An additional line (the instrumented line, IL07), deployed in proximity of the neutrino telescope, hosts a number of devices used for biology, oceanography and geophysics. Temperature, salinity, oxygen content, sound velocity and current speeds are continuously recorded and data sent to the on-shore station. An essential feature of the ANTARES infrastructure is the permanent connection to the shore with the capacity for high-bandwidth acquisition of data. In the short term a significant extension of the multidisciplinary activi-

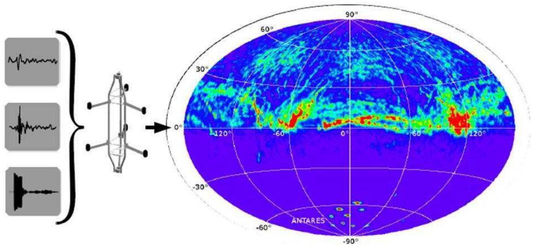

Fig. 6. Map of the angular directions of the detected transient acoustic signals at the ANTARES site.

ties is planned and in the longer term a major extension of all aspects of the undersea observatory is envisioned.

6 Conclusions

In May 2008 the construction of ANTARES, the first deep sea neutrino telescope was completed. A number of selected analyses have been presented based on data from intermediate and full detector configurations. ANTARES is also a multidisciplinary observatory in the Mediterranean Sea, hosting the prototype for an acoustic detection system and several marine science devices. The successful operation of ANTARES and the analyses of its data are an important step towards KM3NET, a future km3-scale high energy neutrino observatory and marine sciences infrastructure planned for construction in the Mediterranean Sea.

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