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All flavour point-source search with the ANTARES neutrino telescope

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Abstract. ANTARES is the largest neutrino telescope in the Northern Hemisphere. The detector has established excellent pointing resolution for muon neutrinos (0.4 degrees) and a degree-level resolution also for contained shower events (about 2 degrees). Together with its geographical location, the good angular resolution makes ANTARES an excellent tool to test for the presence of cosmic sources in the Southern Hemisphere and in particular the area around the Galactic Centre, where IceCube reports a number of high-energy events. In this contribution, we present a search for cosmic neutrino sources using ANTARES data taken from early 2007 until the end of 2013. Such sources are identified as a cluster of events in the combined track and shower channels. In addition to the all-flavour full-sky and candidate list searches, we focus on a restricted region around the Galactic Centre. Different spectral indices for the neutrino energy spectrum have been investigated as well as possible extended sources.

1. Introduction
Many types of astrophysical objects have been proposed to be the production site of high-energy neutrinos through the decay of charged pions which are produced by the interactions of nuclei with ambient matter or radiation. In contrast to cosmic rays, the electrically neutral neutrinos are not deflected by galactic and intergalactic magnetic fields and point straight back to their production site. Detecting high-energy neutrinos and attributing them to a common source would also be strong, indirect evidence for a site of cosmic ray acceleration, the origin of which is one of the oldest questions in astrophysics.

2. The ANTARES detector
ANTARES [1] is the largest neutrino detector in the northern hemisphere and the world’s first deep sea neutrino telescope. It is situated in the Mediterranean Sea at a depth of about 2400 m; approximately 40 km off shore of Toulon, France at, 42° 48' N, 6° 10' E. The detector was completed in mid 2008. It consists of 12 lines with a length of about 450 m. Every line holds 75 optical modules (OMs) in triplets with a distance of about 14.5 m between each group. The OMs face 45° downward to increase the sensitivity to upgoing neutrinos. The upper 5 storeys of line 12 hold acoustic hardware and are not equipped with any OMs. This results in a total of 885 OMs in the detector’s final configuration.

3. Detection Principle
When neutrinos interact with the matter surrounding the detector, they can create charged particles which induce – if created with sufficient energy – Cherenkov Radiation. The radiation is emitted under a characteristic angle of \( \vartheta_c \approx 42° \) in water. These Cherenkov photons get picked up by the detector’s
OMs. The detection time and the measured charge are stored and used for the reconstruction later. The algorithm best suited for this task depends on the type of particles created in the interaction.

**Muon Tracks:** The muons created in muon neutrino charged current interactions can travel straight for several kilometres. Along their track, they induce Cherenkov radiation. The timing of the detected photons is used to reconstruct the parent neutrino’s direction with an accuracy below 0.5° [2].

**Shower Events:** Virtually every other neutrino interaction creates a cascade of charged particles. Such showers extend only a few metres and can be approximated as point sources of light compared to the extent of the detector. The shower reconstruction makes use of the charge distribution in the recorded hits and achieves a median angular resolution of about two degrees [3].

4. **Data Set**
A dedicated run-by-run simulation [4, 5, 6], that replicates the detector and environment conditions during the data taking, is used to optimise the event selection criteria and estimate the signal acceptance and background contamination. The number of selected hits in data compared to the various simulation channels can be seen in figure 2. Selection parameter include i.a. the quality parameter of the fit, the estimated angular error and the reconstructed zenith angle.

For this analysis, ANTARES data from early 2007 until the end of 2013 has been used. In these data – corresponding to a live time 1690 days – 6490 muon tracks and 172 shower events have been selected.

5. **Search Method**
The signature of a neutrino point-source is a cluster of events. To find such a cluster, the following likelihood function has been maximised:

\[
    \log L_{s+b} = \sum_S \sum_{i \in S} \log \left[ \mu_{\text{sig}}^S \cdot F^S(\xi_i) \cdot N_{\text{sig}}^S(N_i) + B^S(\delta_i) \cdot N_{\text{bkg}}^S(N_i) \right] - \mu_{\text{sig}}^S
    + \mathcal{P}(\mu_{\text{sig}} | \mu_{\text{tr}}^{\text{sig}} \cdot A^{\text{sig}}(\delta_s)/A^{\text{tr}}(\delta_s))
\]

- \(F\) – point-spread function
- \(B\) – background rate
- \(N\) – selected hits distribution
- \(S\) – track/shower channel
- \(\delta\) – declination
- \(\xi\) angular distance to source
- \(\mu_{\text{sig}}\) – number of signal events

*Figure 1.* Cumulative distribution of the angular error \(\xi\) of the track reconstruction (left) and the median angular error for different neutrino energies for the shower reconstruction (right).
Figure 2. Number of selected hits by the reconstruction algorithms for muon tracks (left) and showers (right). The different Monte Carlo channels, atmospheric muons (gray), atmospheric neutrinos (red), cosmic neutrinos producing showers (orange) and cosmics neutrinos producing muon tracks (blue), are compared to data (black dots).

Figure 3. The sky map with all selected track and shower events in equatorial coordinates (left) and the sensitivity to neutrino point-sources (right).

6. Results

A sky map of all selected events can be seen on the left hand side of figure 3. In the full sky search, the most significant cluster was found at right-ascension $\alpha = -47.0^\circ$ and declination $\delta = -65.0^\circ$. The cluster’s significance is 4.2% or 2.0$\sigma$. It contains 17 (7) tracks within 3° (1°) and 1 shower event within 10°. The number of signal events found by the likelihood function is $\mu_{\text{tr}}^{\text{sig}} + \mu_{\text{sh}}^{\text{sig}} = 7.3 + 0.0$.

The right plot in figure 3 shows the sensitivity and upper limits on known, fixed source candidates of this combined search as red line and dots. The sensitivity reaches as low as $7 \times 10^{-9}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ for the lower hemisphere. The projected sensitivity including two additional years of data taking are shown as well as a dashed line. The sensitivity to a flux with a hard energy cut-off at $E_{\nu} = 100$ TeV and the sensitivities reported by IceCube are shown as well.

References