Search for a diffuse flux of high-energy muon neutrinos with the ANTARES neutrino telescope

FABIAN SCHÜSSLER[1] ON BEHALF OF THE ANTARES COLLABORATION
[1] *Commissariat à l'énergie atomique et aux énergies alternatives*
Institut de recherche sur les lois fondamentales de l'Univers
91191 Gif-sur-Yvette Cedex, France
fabian.schussler@cea.fr
DOI: 10.7529/ICRC2011/V04/0237

Abstract: We present the search for the diffuse flux of astrophysical muon neutrinos using data collected by the ANTARES neutrino telescope. We introduce a novel method to estimate the energy of high-energy muons traversing the ANTARES detector and discuss detailed comparisons between data and Monte Carlo simulations. Using data recorded in 2008 and 2009 a search for a high-energy excess over the expected atmospheric neutrino background is presented and stringent limits on the diffuse flux of astrophysical muon neutrinos in the energy range 20 TeV - 2.5 PeV are derived.

Keywords: neutrino astronomy, neutrino telescopes, diffuse flux

1 Introduction

Despite enormous efforts throughout the last century, the mystery of the origin of high-energy cosmic rays remains unsolved. Over the last years it became more and more obvious that multiple messengers will be needed to achieve this task. Fortunately fundamental particle physics processes like the production and subsequent decay of pions in interactions of high-energy particles predict clear links between high-energy cosmic rays and high-energy neutrinos as well as gamma rays. The detection of astrophysical neutrinos and the identification of their sources is one of the main aims of large neutrino telescopes operated in ice at the South Pole (IceCube) and in water at Lake Baikal and in the Mediterranean Sea (ANTARES).

1.1 The ANTARES neutrino telescope

The ANTARES detector [1] became fully equipped and operational in 2008. The detector is composed of 12 detection lines placed at a depth of 2475m off the French coast near Toulon. The detector lines are arranged on the seabed in an octagonal configuration, covering a base of $180 \times 180\ \mathrm{m}^2$ and are about 450m high. They hold a total of 885 optical modules (OM), 17" glass spheres housing each a 10" photomultiplier tube. The OMs look downward at 45° in order to optimize the detection of upgoing, i.e. neutrino induced, tracks. The geometry and size of the detector make it sensitive to neutrinos in the TeV-PeV energy range. A schematic layout is shown in Fig. 1.

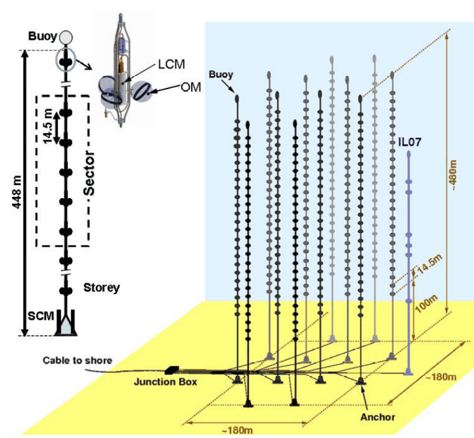

Figure 1: Schematic view of the ANTARES detector.

1.2 Neutrino detection and dataset

The neutrino detection relies on the emission of Cherenkov light by high-energy muons originating from charged current neutrino interactions near and inside the instrumented volume. All detected signals are transmitted via an optical cable to a shore station, where a farm of CPUs filters the data for coincident signals or *hits* in several adjacent OMs. The muon direction is then determined by maximising a likelihood which compares the times of the hits with the expectation from the Cherenkov signal of a muon track.

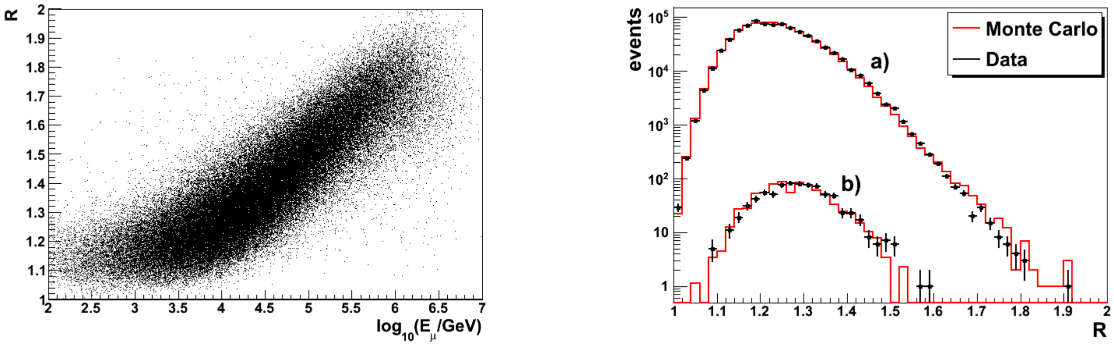

Figure 2: Left plot: Correlation between the energy estimator R and the generated muon energy after all quality cuts. Right plot: Distribution of the R energy estimator of data (markers) and simulated atmospheric muons normalized to the data (histograms) applying only loose quality cuts. Good agreement of the shape is found for both downgoing muons (a) and events mis-reconstructed as upgoing (b).

We analyse here data taken with the ANTARES detector between 12/2007 and 12/2009. Related to the construction and maintenance efforts, this period includes data from a detector comprised of 9, 10 and 12 active detection lines. Data runs were selected according to a set of basic quality criteria, which require for example low environmental background noise. The selection corresponds to a total live time of 334 days (136 days with 9 lines, 128 days with 10 lines and 70 days with 12 lines).

2 Diffuse astrophysical neutrino flux

The measured flux of high-energy cosmic rays has been used to derive upper bounds for the expected diffuse neutrino flux [2, 3]. For the TeV to PeV energy range considered here, this flux is typically assumed to originate from particle interactions at or close to the cosmic ray acceleration sites. Although only weakly constrained, the neutrino energy spectrum is typically modelled by a simple E^{-2} power law.

2.1 Background discrimination

Two main backgrounds for the measurement of the flux of these astrophysical neutrinos can be identified: downgoing atmospheric muons which have been mis-reconstructed as upgoing and atmospheric neutrinos originating in cosmic ray induced air showers at the opposite side of the Earth. Both backgrounds can at least partially be discriminated using various parameters like the quality of the event reconstruction or an estimator for the energy of the muon. To optimize the selection criteria detailed Monte Carlo (M-C) simulations have been used. The atmospheric muon flux has been simulated with the MUPAGE package [4]. Generated atmospheric neutrinos are weighted corresponding to the 'Bartol' parametrisation [5]. Due to the lack of information on the production of charm mesons in high-energy hadronic interactions, the presence of an additional component at high energies (above $\sim$ 10 TeV) is possible. Among the models considered in [6] the Recombination Quark Parton Model (RQPM) was used. It gives the largest 'prompt' contribution to the atmospheric neutrino flux. Both event types, atmospheric muons and neutrinos, are processed with the full ANTARES detector simulation and reconstruction chain. Special care has been taken to reproduce the changing detector configuration during the analysed data taking period and the details of the data acquisition by including for example afterpulses in the PMT simulations. The simulated instrumental and environmental background noise has been extracted for each of the detector configurations from a representative real data-taking run.

2.2 Atmospheric muon rejection

Atmospheric muons are recorded with the ANTARES detector at a rate of several Hz and dominate the detector trigger rate. To remove a large majority of them from the dataset the selected events have to fulfil the following basic quality criteria:

- detection with at least two detector lines
- more than 60 hits available for the reconstruction
- reconstructed zenith angle $\theta < 80°$, i.e. upgoing tracks

To fully suppress mis-reconstructed atmospheric muons, an additional 2-dimensional cut has been derived. It combines the quality parameter Λ which is derived from the likelihood value of the track fitting algorithm and the number of hits used in the fitting procedure N_{hit}. The events have to pass the selection

$$\Lambda > \begin{cases} -4.59 - 5.88 \cdot 10^{-3}\, N_{\mathrm{hit}} & \text{for} \quad N_{\mathrm{hit}} \leq 172 \\ -5.60 & \text{for} \quad N_{\mathrm{hit}} > 172 \end{cases}$$

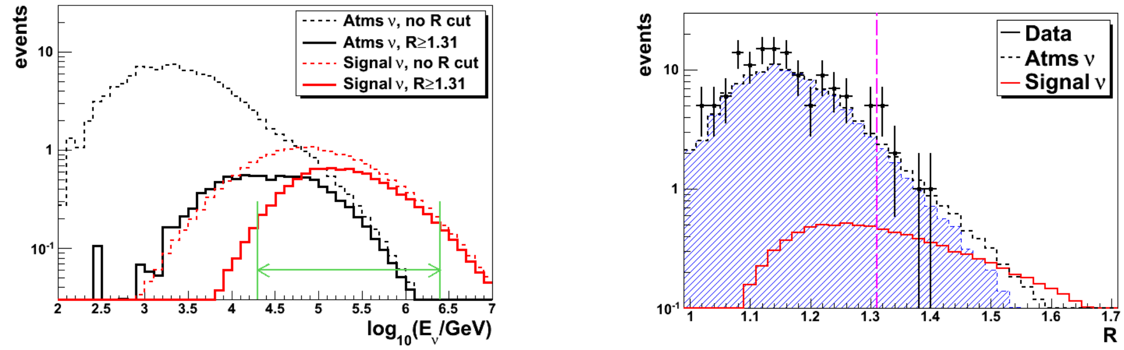

Figure 3: Left plot: Energy distribution for the Bartol+RQPM atmospheric neutrino flux and a E^{-2} astrophysical signal with arbitrary normalisation after all quality cuts. The horizontal arrow denotes the interval in which 90% of the signal events is expected. Right plot: Distribution of the energy estimator R for data (markers), the Bartol atmospheric neutrino flux (filled histogram) and the 'prompt' contribution (RQPM model, dashed histogram). The signal at the level of the derived upper limit is shown as the full, red line together with the cut at $R > 1.31$ (vertical, dashed line).

Applied to Monte Carlo simulations, these cuts completely remove the $2 \cdot 10^8$ reconstructed tracks induced by atmospheric muons and reduce the contribution from atmospheric neutrinos (Bartol + RQPM) from $7 \cdot 10^3$ to 116 events [7].

2.3 Energy estimator

As the flux of astrophysical neutrinos is expected to follow a harder spectrum ($\propto E^{-2}$) than that of the atmospheric neutrino background it should become visible as an excess of high-energy events. This discrimination requires an estimation of the neutrino, or as best approximation, the muon energy. Various energy estimators are under study within the ANTARES collaboration [8]. Here we exploit the structure of the arrival times of photons created along the muon track at the OMs. This time structure is sensitive to the energy as higher energy muons have a higher probability to create electromagnetic showers along the track. The light emitted by these showers is responsible for delayed hits in the OMs with respect to the detected Cherenkov photons. A robust parameter sensitive to delayed photons is the mean number of hit repetitions R within an event. It is calculated by averaging the number of hits R_i recorded by an OM within a 500 ns time window over all OMs contributing to the reconstructed muon track. The clear correlation with muon energy is shown for simulated events in Fig. 2, left plot. The estimator has been extensively studied both on MC and on (atmospheric muon dominated) data (e.g. Fig. 2, right plot) and an average HWHM resolution after the discussed quality criteria of $\log(E_{\rm rec}/E_{\rm true}) = 0.4$ could be determined.

2.4 Optimisation of the event selection

The final discrimination between the atmospheric neutrino background and the astrophysical signal is achieved by a cut in the R variable. This cut has been optimized before un-blinding the data by minimizing the Model Rejection Factor (MRF) [9]. Taking into account all possible fluctuations of the number of background events $n_{\rm B}$, the average upper limit $\bar{\mu}_{90\%}(n_{\rm B})$ of background-only pseudo-experiments is derived. The optimal value of the cut in R is then determined by minimizing the MRF given as $\bar{\mu}_{90\%}(n_{\rm B})/n_{\rm S}$, where $n_{\rm S}$ is the number of expected signal events from an E^{-2} test spectrum. The optimum has been found when selecting events above $R_{\rm cut} = 1.31$.

The determination of the energy estimator cut allows to define the energy range to which the analysis will be sensitive. We define this range as the interval containing 90% of the signal events and obtain $20\ {\rm TeV} < E_\nu < 2.5\ {\rm PeV}$ (see Fig. 3, left plot).

2.5 Low energy region and systematic uncertainties

Before un-blinding the data in the defined region $R > 1.31$ the distribution of the selected data events below this cut has been compared to the corresponding Monte Carlo simulations. Whereas 125 events are selected from data, the Bartol flux parametrisation combined with the RQPM model for the prompt contribution predicts 105 events. The observed difference is well within the systematic uncertainty of the atmospheric neutrino flux given as $25 - 30\%$ [10] and has been corrected before un-blinding the high-energy region by applying a scale factor $k = 105/125 = 1.19$ to the MC predictions.

Further systematic uncertainties on the number of expected events in the high-energy signal region include

- the contribution of prompt events derived as maximal deviation between the models discussed in [6] of $^{+1.7}_{-0.3}$ events. The maximal value (1.7 events) is used in the following.

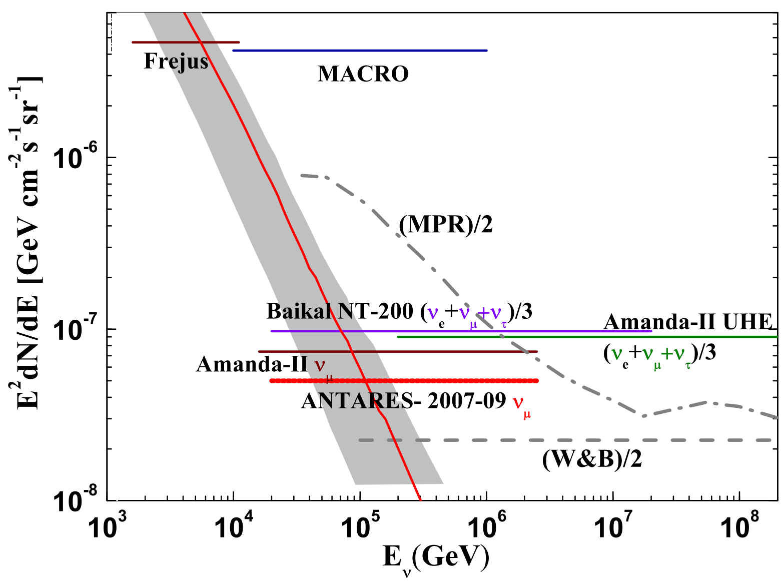

Figure 4: The upper limit for a E^{-2} diffuse high-energy $\nu_\mu + \bar{\nu}_\mu$ flux derived from data of the ANTARES neutrino telescope compared to previous measurements and phenomenological upper bound predictions.

- uncertainties in the spectral shape of the atmospheric neutrino flux which is related to uncertainties in the primary cosmic ray energy spectrum. By varying the spectral index of the neutrino spectrum by ± 0.1 independently below and above ≈ 10 TeV we obtained a sys. uncertainty of ± 1.1 events.
- uncertainties in the details of the description of the detector and environmental parameters like the angular acceptance of the OMs, details of PMT afterpulses and water properties like absorption and scattering lengths which lead to a total uncertainty of 5%.

3 Results

Applying the discussed quality and energy selection criteria to the simulated dataset gives a background estimation of $n_\mathrm{B} = 10.7 \pm 2$ events in the high-energy region. In the analysed dataset of the ANTARES detector 9 events were selected. Including the systematic uncertainty on the background expectations following the method discussed in [11] we derive the 90% c.l. upper limit on the number of signal events as $\mu_{90\%}(n_\mathrm{B}) = 5.7$. The corresponding upper limit on the neutrino flux is given by $\phi_{90\%} = \phi \cdot \mu_{90\%}/n_\mathrm{S}$, where n_S is the number of events expected from the flux ϕ. We obtain [12]:

$$E^2\phi_{90\%} = 5.3 \times 10^{-8}\ \mathrm{GeV^{-2}s^{-1}sr^{-1}} \qquad (1)$$

As can be seen in Fig. 4, the derived limit is competitive with previous results and further constrains models of the diffuse flux high-energy $\nu_\mu + \bar{\nu}_\mu$ flux.

References

[1] M. Ageron *et al.* (ANTARES Collaboration), ANTARES: the first undersea neutrino telescope, to appear in NIM A (2011)

[2] E. Waxman, J. Bahcall, Phys. Rev. D 59 (1998) 023002 J. Bahcall, E. Waxman, Phys. Rev. D 64 (2001) 023002

[3] K. Mannheim, R.J. Protheroe, J.P. Rachen, Phys. Rev. D 63 (2000) 023003

[4] Y. Becherini, A. Margiotta, M. Sioli, M. Spurio, Astropart. Phys. 25 (2006) 1
G. Carminati, M. Bazzotti, A. Margiotta, M. Spurio, Comp. Phys. Comm. 179 (2008) 915

[5] V. Agrawal, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. D 53 (1996) 1314

[6] C.G.S. Costa, Astropart. Phys. 16 (2001) 193

[7] S. Biagi, proceedings CRIS 2010 (Nucl. Phys. B proc. suppl. 212-214)

[8] D. Palioselitis for the ANTARES Collaboration, Muon energy reconstruction and atmospheric neutrino spectrum unfolding with the ANTARES detector, these proceedings, 2011

[9] G.C. Hill, K. Rawlins, Astropart. Phys. 19 (2003) 393

[10] Barr, G. D., Robbins, S., Gaisser, T. K. and Stanev, T., Phys. Rev. D 74 (2006) 094009

[11] J. Conrad, et al., Phys. Rev. D 67 (2003) 012002

[12] J.A. Aguilar *et al.* (ANTARES Collaboration), Physics Letters B 696 (2010) 16