Upper Limit on the Diffuse Flux of Cosmic $\nu_{\mu}$ with the ANTARES Neutrino Telescope

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A search for a diffuse flux of astrophysical muon neutrinos, using data collected by the ANTARES neutrino telescope from December 2007 to December 2009 is presented. 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, over the expected atmospheric neutrino background without any particular assumption on the source direction. Since the number of detected events is compatible with the number of expected background events, a 90% c.l. upper limit on the diffuse $\nu_{\mu}$ flux with a $E^{-2}$ spectrum is set at $E^2\Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy range $20$ TeV – $2.5$ PeV. Other signal models with different energy shape were also tested and some rejected.

1. Introduction

The ANTARES high-energy neutrino telescope is a three-dimensional array of photomultiplier tubes (PMT) distributed over 12 lines installed deep in the Mediterranean Sea, each line including 75 PMTs [1]. A neutrino telescope in the Northern hemisphere includes the Galactic Centre in its field of view and is complementary to the IceCube Antarctic telescope [2].

The main goal of the experiment is the search for high-energy neutrinos from astrophysical sources. If the sensitivity of point source search techniques is too small to detect neutrino fluxes from individual sources, it is possible that many sources could produce an excess of events over the expected atmospheric neutrino background. In this proceeding the search for very-high energy extraterrestrial muon neutrinos from unresolved sources is presented using data collected by the ANTARES telescope from December 2007 to December 2009.

Atmospheric muons and neutrinos are the main sources of background in a neutrino telescope. The former can be suppressed by applying requirements on the direction of the events, the latter is an irreducible background. As the spectrum of cosmic neutrinos is expected to be harder than that of atmospheric neutrinos, the signal we are looking for corresponds to an excess of high energy events in the measured energy spectrum without any particular assumption on the source direction.

Electrons (in the so-called “leptonic models”) or protons and nuclei (“hadronic models”) can be accelerated in astrophysical processes. Hadronic models [3] predict that the energy produced in the sources is carried away by cosmic rays, $\gamma$-rays and neutrinos. A benchmark flux for the measurement of diffuse neutrinos is the Waxman-Bahcall (W&B) upper bound [4]. Using the CR observations at $E_{CR} \sim 10^{19}$ eV ($E_{CR}^2\Phi_{CR} \sim 10^{-8}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$) the diffuse flux of muon neutrinos is constrained at the value:

$$E^2\nu\Phi_{\nu} < 4.5/2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \quad (1)$$

(the factor $1/2$ is added to take into account neutrino oscillations).

2. Neutrino tracking and energy reconstruction

Muon neutrinos are detected via charged current interactions: $\nu_{\mu} + N \rightarrow \mu + X$. The arrival times and the amplitudes of the Cherenkov light signals detected by the PMTs [5] are used to re-
construct the trajectory of muon neutrinos and to estimate their energy.

The track reconstruction algorithm defined in [6] is based on a likelihood fit that uses a detailed parametrization of the probability density function for the photon arrival times. The track position and direction, the information on the number of hits \(N_{\text{hit}}\) used for the reconstruction and a quality parameter \(\Lambda\) are the main outputs of the algorithm. \(\Lambda\) is determined from the likelihood and the number of compatible solutions found by the algorithm itself. \(\Lambda\) can be used to reject badly reconstructed events. For \(E_\nu > 10\) TeV, an angular resolution for muon neutrinos better than \(0.3^\circ\) is accomplished by the ANTARES detector.

### 2.1. Monte Carlo simulations

The Monte Carlo (MC) simulation tools [7,8] include the production of Cherenkov light, the generation of the optical background caused by radioactive isotopes and bioluminescence present in sea water, and the digitization of the PMT signals. In particular, the PMT simulation also includes the probability of a detected hit giving rise to an afterpulse. The simulation of afterpulses is critical when the energy estimator defined in §2.2 is applied to MC events. The afterpulse probability was measured in laboratory using ANTARES [9] and NEMO [10] PMTs and it was confirmed with deep-sea data. Upgoing muon neutrinos and downgoing atmospheric muons have been simulated and stored in the same format used for the data.

**Signal and atmospheric neutrinos.** MC muon neutrino events have been generated in the energy range \(10 \leq E_\nu \leq 10^8\) GeV and zenith angle between \(0^\circ \leq \theta \leq 90^\circ\) (upgoing events). The same MC sample can be differently weighted to reproduce the “conventional” atmospheric neutrino spectrum (Bartol), \(\propto E_\nu^{-3.7}\) at high energies [11], and the expected astrophysical signal spectrum, \(\propto E_\nu^{-2}\). The normalization of the signal flux is irrelevant when defining cuts, optimizing procedures and calculating the sensitivity. Here a diffuse flux test signal is defined equal to:

\[
E_\nu^2 \Phi_\nu = 1.0 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \tag{2}
\]

Above 10 TeV, the semi-leptonic decay of short-lived charmed particles \(D \rightarrow K + \mu + \nu_\mu\) becomes a significant source of atmospheric “prompt leptons”. The Recombination Quark Parton Model (RQPM) is used in this simulation, since it gives the largest prompt contribution among the models considered in [12].

**Atmospheric muons.** The ANTARES trigger rate [13] is dominated by atmospheric muons that represent the main background for a neutrino telescope. A small fraction (approximately 5%) of triggered downgoing muons is mis-reconstructed as upgoing; their rejection is a crucial point in this analysis.

The MUPAGE package [14] was used to simulate atmospheric muon samples. One year of equivalent live time with a total energy \(E_T \geq 1\) TeV and bundle multiplicity \(m = 1 \div 1000\) was generated. The total energy \(E_T\) is the sum of the energy of the individual muons in an atmospheric muon bundle. Triggered ANTARES events mainly consist of multiple muons originating in the same primary CR interaction [15].

### 2.2. Energy dependent variable

The only way to separate atmospheric and astrophysical neutrinos is through a discrimination based on the energy. An original energy estimator is defined, which is based on hit repetitions in the PMTs due to the different arrival time of direct and delayed photons (Fig. 1). Direct photons are emitted at the Cherenkov angle and arrive at the PMTs without being scattered. Radiative processes contribute to energy losses linearly with
the muon energy for $E_\mu > 1$ TeV. The resulting electromagnetic showers produce additional light. Photons originating from secondary electromagnetic showers or scattered Cherenkov radiation arrive on the PMTs delayed with respect to the direct photons, with arrival time differences up to hundreds of ns \cite{3}. The fraction of delayed photons increases with the muon energy.

The signal produced by the PMTs is processed by two Analogue Ring Sampler (ARS) \cite{16} which digitize the time and the amplitude of the signal (the hit). They are operated in a token ring scheme. If the signal crosses a preset threshold, typically 0.3 photo-electrons, the first ARS integrates the pulse within a window of 40 ns. If triggered, the second chip provides a second hit with a further integration window of 40 ns. After digitization, each chip has a dead time of typically 250 ns. After this dead time, a third and fourth hit can also be present.

The number of repetitions $R_i$ for the $i$-th PMT is defined as the number of hits in the same PMT within 500 ns from the earliest hit selected by the reconstruction algorithm (Fig. 1). In most cases, $R_i = 1$ or 2, but it could be also 3 or 4. The mean number of repetitions in the event is defined as $R = \frac{\sum R_i}{N_{PMT}}$, where $N_{PMT}$ is the number of PMTs in which hits selected by the tracking algorithm are present. For a muon neutrino sample, $R$ is linearly correlated with the log of the true muon energy $E_{true}$ in the range from 10 TeV ($\bar{R} \simeq 1.26$) to 1 PeV ($\bar{R} \simeq 1.73$). $R$ can be used to estimate the muon energy $E_{reco}$, see Fig. 2. The distribution of $\log(E_{reco}/E_{true})$ has a FWHM=0.8. The resolution is comparable or better with respect to other energy reconstruction algorithm \cite{17}.

This energy estimator is robust because it does not depend on the number of active PMTs and on non-linear effects on charge integration.

### Table 1

|               | $\mu_{atm}$ | $\nu_{atm}$ | $\nu_{sig}$ | Data |
|---------------|-------------|-------------|-------------|------|
| Reco          | $2.2 \cdot 10^3$ | $7.1 \cdot 10^3$ | 106 | $2.5 \cdot 10^8$ |
| Upgoing       | $4.8 \cdot 10^6$ | $5.5 \cdot 10^3$ | 80 | $5.2 \cdot 10^6$ |
| 1st-level     | $9.1 \cdot 10^3$ | 142 | 24 | $1.0 \cdot 10^4$ |
| 2nd-level     | 0 | 116 | 20 | — |

Expected events in 334 days of equivalent live time for the three MC samples: atmospheric muons, atmospheric neutrinos (Bartol+RQPM), astrophysical signal from eq. 2 and data. Reco: at the reconstruction level; Upgoing: reconstructed as upgoing; 1st-level: after the first-level cuts; 2nd-level: after the second-level cut.

### 3. Cosmic neutrino signal selection

The data collected from December 2007 to December 2009 are analyzed. In this period, the detector configuration changed several times with 9, 10 and 12 active lines. For this reason, three different detector configurations, based on the number of active lines and optical modules, were reproduced in MC simulations. Data runs are selected according to the data-quality requirements explained in \cite{8}. The total live time is 334 days: 70 days with 12 lines, 128 days with 10 lines and 136 days with 9 lines.

#### 3.1. Rejection of atmospheric muons

As described in \cite{2,1} the rejection of atmospheric muons is a crucial point in the search for a cosmic neutrino signal. This contamination can be strongly suppressed by applying requirements on the geometry of the events and on the track reconstruction quality parameter $\Lambda$. Two different levels of cuts are defined in order to remove the
contamination of mis-reconstructed atmospheric muons from the final sample.

**First-level cuts.** Events are selected according to these criteria: (i) upgoing particles with reconstructed zenith angle \( \theta_{\text{rec}} < 80^\circ \) (corresponding to \( 0.83 \times 2\pi \) sr); (ii) \( \Lambda > -6 \); (iii) \( N_{\text{hit}} > 60 \); (iv) reconstruction with at least two lines. The first-level cuts reduce the rate of mis-reconstructed events by almost 3 orders of magnitude, as indicated in Table 1.

**Second-level cut.** The remaining atmospheric muons have the quality parameter \( \Lambda \) which on average decreases with increasing \( N_{\text{hit}} \). Fig. 3 (left) shows the correlation between \( \Lambda \) and \( N_{\text{hit}} \) for atmospheric muons. In order to completely remove the expected rate of mis-reconstructed events in the MC sample, a cut value \( \Lambda^* \) is defined as a function of \( N_{\text{hit}} \):

\[
\Lambda^* = \begin{cases} 
-4.59 - 5.88 \times 10^{-3} N_{\text{hit}} & N_{\text{hit}} \leq 172 \\
-5.60 & N_{\text{hit}} > 172
\end{cases}
\]  

Removing all events with \( \Lambda < \Lambda^* \), the atmospheric muons are completely suppressed. Independent MC atmospheric muon simulations using CORSIKA (see details in \[8\]) confirm that the maximum contamination in the final sample is less than 1 event/year. As can be seen in Fig. 3 (right), the signal is highly preserved from the second-level cut. The effects of the first- and second-level cuts on signal and atmospheric neutrinos are also given in Table 1.

### 3.2. Discrimination from atmospheric neutrinos

A cut on the energy dependent variable \( R \), defined in \[22\], is used to separate the diffuse flux signal from the atmospheric \( \nu_\mu \) background. The optimal cut value is obtained through a blinding procedure on MC events, without using informations from the data. The numbers of expected signal (\( n_s \)) and background (\( n_b \)) events are computed as a function of \( R \). Then, calculating the so-called Model Rejection Factor (MRF) defined in \[18\], the best cut is obtained and used as the discriminator between low energy events, dominated by the atmospheric neutrinos, and high energy events, where the signal could exceed the background. After the optimization of all the parameters, the observed data events (\( n_{\text{obs}} \)) are revealed (un-blinding procedure) and compared with the expected background for the selected region of \( R \). If data are compatible with the background, the upper limit for the signal flux is calculated using the Feldman-Cousins method \[19\] at a 90% confidence level (c.l.).

The cumulative distributions of the \( R \) variable for atmospheric neutrino background (Bartol+RQPM) and diffuse flux signal (eq. 2) are computed for the three configurations of the ANTARES detector and the corresponding live times. The MRF is calculated as a function of \( R \) using these cumulative distributions. The minimum found for \( R = 1.31 \) determines the cut value.
for the energy dependent variable [20]. Assuming the Bartol (Bartol+RQPM) atmospheric $\nu_\mu$ flux, 8.7 (10.7) background events and 10.8 signal events are expected for $R \geq 1.31$. The central 90% of the signal is found in the neutrino energy range 20 TeV $< E_\nu < 2.5$ PeV.

4. Upgoing neutrino candidates

4.1. Low energy events $R < 1.31$

Events surviving the second-level cut are upgoing neutrino candidates. The first step of the un-blinding is to reveal the events with $R < 1.31$. In this region, 125 events are found. A comparison with MC predictions is shown in Fig. 4 as a function of $R$. The events with $R \geq 1.31$ in Fig. 4 are uncovered after the final un-blinding of the data sample. MC predictions are lower by $\sim 20\%$ with respect to the detected events. Bartol atmospheric neutrino MC predicts 104.0 events with $R < 1.31$, and Bartol + RQPM predicts 105.2 events. The discrepancies between predicted and measured events are well within the systematic uncertainties of the absolute neutrino flux at these energies (25-30%) [11].

The number of expected background events with $R \geq 1.31$ is 8.7 for Bartol MC only. Most prompt models described in [12] give negligible contributions; the RQPM model predicts the largest contribution of 2.0 additional events with respect to the conventional Bartol flux. An average over all the considered models gives a contribution of 0.3 events. A combined model of Bartol flux plus the average contribution from prompt models is adjusted with the data/MC normalization factor obtained in the $R < 1.31$ region. Hence the number of expected background events for $R \geq 1.31$ is 10.7.

4.2. High energy events and upper limit

The MC simulations have been tested and compared with data. In particular, the $R$ distributions show a reasonable agreement both for atmospheric muons [20] and for atmospheric neutrinos in the low energy region $R < 1.31$ (c.f. Fig. 3). As a consequence, the signal region with $R \geq 1.31$ was un-blinded and 9 high-energy neutrino candidates are found.

Systematic uncertainties on the expected number of background events in the $R \geq 1.31$ region are evaluated considering: (i) the contribution of prompt neutrinos, estimated as $+1.7 -0.3$ events; (ii) the uncertainties from the conventional neutrino flux, that depend mainly on the uncertainty on the absolute flux as a function of the energy and on the spectral index, evaluated to be $\pm 1.1$ events. The uncertainties on the detector efficiency (angular acceptance of the optical module, water absorption, scattering length, trigger simulation and the effect of afterpulses) amount to 5%; they affect the detection both of signal and background neutrinos in the high energy region.

The number of observed events is compatible with the number of expected background events. The 90% c.l. upper limit on the number of signal events $\mu_{90\%}(n_{obs}, n_b)$ for $n_{obs} = 9$ observed events and $n_b = 10.7 \pm 2$ background events including the systematic uncertainties is computed with the method of [21]: the value $\mu_{90\%}(n_b) = 5.7$ is obtained. The upper limit on the diffuse flux is given by

$$E^2 \Phi_{90\%} = 5.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  (4)
This limit holds for the energy range between 20 TeV to 2.5 PeV. The result is compared with other measured flux upper limits and theoretical predictions in Fig. 5.

Some theoretical predictions of cosmic neutrino fluxes with a spectral shape different from $E^{-2}$ are also tested. For each model a cut value $R^*$ is optimized following the procedure in [3]. Table 2 gives the results for the models tested: the values of $R^*$, the numbers $N_{mod}$ of $\nu_\mu$ signal events for $R \geq R^*$, the energy intervals where 90% of the signal is expected, the ratios between $\mu_{90\%}$ (computed according to [19]) and $N_{mod}$. A value of $\mu_{90\%}/N_{mod} < 1$ indicates that the theoretical model is inconsistent with the experimental result at the 90% c.l. [20].

5. Conclusions

Using data from 334 days of equivalent live time collected with the ANTARES telescope, a search for a diffuse flux of high energy cosmic muon neutrinos was made. The 90% c.l. upper limit on the diffuse $\nu_\mu$ flux with a $E^{-2}$ spectrum is set at $E^2 \Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ in the energy range 20 TeV – 2.5 PeV. Other signal models with different energy shape are also tested and some of them excluded at the 90% c.l.

Table 2

| Model      | $R^*$ | $N_{mod}$ | $\Delta E_{90\%}$ (PeV) | $\mu_{90\%}/N_{mod}$ |
|------------|-------|-----------|--------------------------|-----------------------|
| MPR        | 1.43  | 3.0       | 0.1\pm0.10              | 0.4                   |
| P96\gamma  | 1.43  | 6.0       | 0.2\pm0.10              | 0.2                   |
| SO5        | 1.45  | 1.3       | 0.3\pm0.5               | 1.2                   |
| SeSi       | 1.48  | 2.7       | 0.3\pm0.20              | 0.6                   |
| Mpp + p\gamma | 1.48 | 0.24     | 0.8\pm0.50              | 6.8                   |

Astrophysical flux models, the value of the $R^*$ which minimizes the MRF, the expected number of events $N_{mod}$, the energy range $\Delta E_{90\%}$ in which the 90% of events are expected, and the ratio $\mu_{90\%}/N_{mod}$. See [20] and references therein.

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