PROCEEDINGS OF SCIENCE

Moon shadow observation with the ANTARES neutrino telescope

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The ANTARES detector is the largest neutrino telescope currently in operation in the North Hemisphere. One of the main goals of the ANTARES telescope is the search for point-like neutrino sources. For this reason both the pointing accuracy and the angular resolution of the detector are important and a reliable way to evaluate these performances is needed. One possibility to measure the angular resolution and the pointing accuracy is to analyse the shadow of the Moon, i.e. the deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays. Analysing the data taken between 2007 and 2012, the Moon shadow is detected with about 3σ significance in the ANTARES data. The first measurement of the ANTARES angular resolution and absolute pointing for atmospheric muons using a celestial calibration source is obtained. The presented results confirm the good pointing performance of the detector as well as the predicted angular resolution.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

PoS(ICRC2015)1138

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1. Introduction

The neutrinos are a unique probe for the investigation of the Universe, they are chargeless, weakly interacting particles that can cross dense matter or radiation fields without being absorbed for cosmological distance. The neutrino detection can provide more information on the nature of far Universe and the interior of the astrophysical sources, their observation can be also combined with multi-wavelength light and charged cosmic measures.

The ANTARES neutrino telescope [1] is the largest neutrino telescope currently in operation in the North hemisphere. It is designed for the detection of high energy cosmic neutrinos and in particular the identification of point-like sources, like starburst galaxies, GRBs, Supernova remnants and AGNs.The pointing accuracy and the angular resolution of the detector are really important for the detection of point-like sources and a proper way to evaluate these performances is needed. Several experiments, like CYGNUS [2], TIBET [3], CASA [4], MACRO [5], SOUDAN [6] , ARGO [7] and IceCube [8], used the so-called Moon shadow effect to test the pointing performance of the detector.

The Moon absorbs part of the cosmic rays, so a deficit in the event density of the atmospheric muon flux corresponding to the direction of the Moon disk is expected. In this work we exploit this technique to measure the ANTARES angular resolution for atmospheric down-going muons and the detector absolute pointing capability.

2. Monte Carlo simulations

The simulation of the atmospheric muon events was performed with the MUPAGE code [9], where the geo-magnetic deflection is not taken into account in the simulation code. In order to take in account this effect a study of the deflection effect has been previously conducted by the collaboration using Corsika code [10]. The correction of the muons trajectory is negligible at detector level because only low energy muons that are absorbed before reaching the detector are strongly deflected [11], so the geo-magnetic effect can be neglected in this analysis.

Muon bundles were generated on the surface of a cylinder-shaped volume of water, called the *can*, containing the detector. It is the volume sensitive to the light and it is 200 m larger than the instrumented volume. The generation of Cherenkov light emitted by the muon tracks is simulated. The simulation includes also optical background caused by bioluminescence and radioactive isotopes present in sea water. The detector response is then simulated [12], the charge of the analogue pulse being evaluated according to the number of photons arriving on each PMT and the charge of consecutive pulses being integrated in a time window of 25 ns. The hit time is defined as the arrival time of the first photon. Finally the standard ANTARES reconstruction algorithm uses the hits detected by the PMT to reconstruct the direction of atmospheric muon tracks. The algorithm is a robust track fitting procedure based on a maximisation likelihood method.

Two different Monte Carlo simulation sets were performed: one considering the shadowing effect of the Moon and the other without this effect. The shadowing effect is simulated rejecting the muons generated within the Moon disk ($R_{Moon} = 0.259°$). The live time of each simulation is the 2080 days period considered in this data analysis (years 2007-2012). The experimental conditions of each data run (PMT status, detector configuration, actual environmental conditions, optical background) are simulated like in the official ANTARES run-by-run simulation [13] . The systematic uncertainties of the primary muon flux and of the detector lead to a discrepancy around 6% between Monte Carlo simulation and data, this behaviour was already shown in other ANTARES analysis [14]. The Monte Carlo simulations were therefore renormalized in order to reproduce the muon data rate in the region were the shadowing effect is expected to be negligible.

The optimization of the selection criteria used in this data analysis will be described in the next section.

3. Detection of the Moon shadow

In order to measure the deficit of muons in the direction of the Moon, the region of the sky around the Moon centre is divided in concentric rings with increasing radius. We define the event density of each ring as the number of events detected in that sector over the surface of the ring. The ring size is 0.2°, so an appropriate investigation of the Moon shadow with sufficient statistics in each annular ring can be performed. Obviously event tracks detected when the Moon is above the Horizon and reconstructed as down-going are selected.

A test statistic function t is defined as:

$$t = \sum_{rings} \frac{(n_m - n_{exp,\ NO\ Moon})^2}{n_{exp,\ NO\ Moon}} - \frac{(n_m - n_{exp,\ Moon})^2}{n_{exp,\ Moon}}, \tag{3.1}$$

where the sum is over all the rings around the Moon centre; n_m is the number of events detected in a ring, $n_{exp,Moon}$ is the expected number of events in “Moon shadow” hypothesis and $n_{exp,NOMoon}$ is the expected number of events in “no Moon shadow” hypothesis. A million of toy experiments were generated to derive the test statistic distribution in the two different hypotheses ("Moon shadow" or "No Moon shadow").

The significance of the Moon shadow deficit was estimated optimising the event selection using the statistical tools previously described. In this analysis quality cuts on the log-likelihood per degree of freedom $\Lambda < \Lambda_{\mathrm{cut}}$ was applied. The maximisation of the significance is found for $\Lambda_{\mathrm{cut}} = -5.9$ as shown in Fig. 1.

The corresponding test function distributions are plotted in Fig. 2. The shaded area gives the fraction of the toy experiments where the Moon shadow hypothesis will be correctly identified as evidence of the shadowing effect; this fraction is fixed to 50%. The value of $t = 6.15$ corresponding to this fraction of the “Moon shadow” toy experiments is the decision boundary of the test statistic. The orange area corresponds to the fraction of “No Moon shadow” toy experiments that will be wrongly identified as evidence of shadowing effect. In other words, this area quantifies the minimum significance of the Moon shadow discovery for experiments with $t > 6.15$. The minimum significance is here 2.9σ.

The same quality cut $\Lambda_{\mathrm{cut}} = -5.9$ was applied to the data set. The value of test statistic function defined in Eq. 3.1 was then computed for data resulting in $t = 7.12$. The “No Moon shadow” hypothesis can be therefore rejected with a significance of 3.1σ.

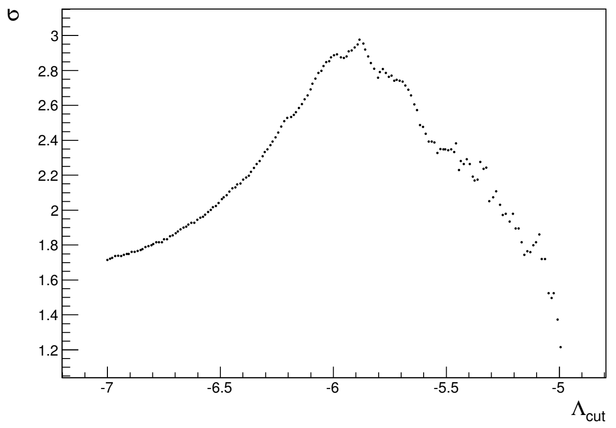

Figure 1: Expected significance (expressed as number of σ) as a function of Λ_{cut}.

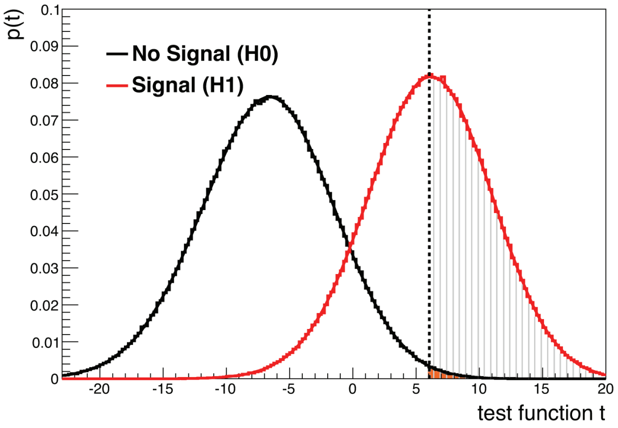

Figure 2: The test function t distribution for "Moon shadow" hypothesis (red curve) and "no Moon shadow" hypothesis (black curve). The shaded area is the fraction of the toy experiments where the Moon shadow hypothesis will be correctly identified as evidence of the shadowing effect. The orange area quantifies the minimum significance (here 2.9σ) to observe the Moon shadow.

4. Angular resolution and absolute pointing

The angular resolution of a neutrino telescope is usually estimated through the Monte Carlo simulations, because there is not an immediate way to estimate this parameter with data. The Moon shadow study represents an unique way to estimate the pointing performance of the detector. The plot of event density for selected muons as a function of the angular distance from the Moon centre is shown in Fig. 3

It is possible to evaluate the detector angular resolution fitting the event density with the formula:

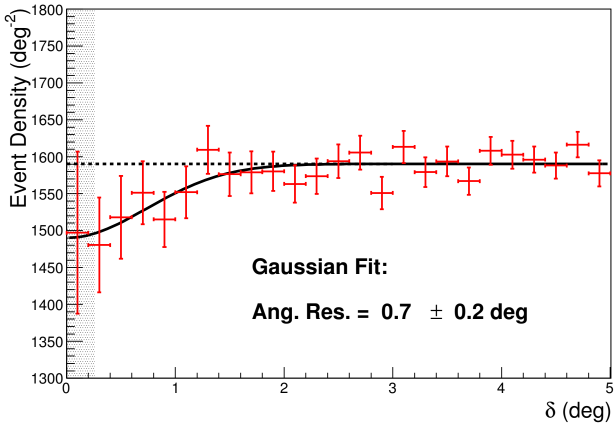

Figure 3: Event density of muons after selection cut versus the angular distance from the Moon centre. The shadow is fitted assuming a Gaussian shape for the detector point spread function. The resulting angular resolution is $\varsigma = 0.7^\circ \pm 0.2^\circ$ for atmospheric muons. The shaded area represents the Moon radius ($R_{Moon} = 0.259^\circ$).

$$\frac{\mathrm{d}n}{\mathrm{d}\delta^2} = k\left(1 - \frac{R^2_{Moon}}{2\varsigma^2} e^{-\frac{\delta^2}{2\varsigma^2}}\right), \tag{4.1}$$

where $R_{Moon} = 0.259^\circ$ is the Moon radius and δ is the angular distance from the Moon centre. The fit free parameters k and ς are respectively the off-source density level and the detector angular resolution. We have assumed a Gaussian shape for the detector point spread function [15]. From the fit we can estimate the angular resolution: $\varsigma = 0.7^\circ \pm 0.2^\circ$.

Finally the ANTARES absolute pointing performance was evaluated. It is possible that if the detector orientation is affected by a systematic error, the Moon shadow will appear shifted respect to the expected position. In order to investigate this possibility, the concentric rings around the Moon centre are shifted (see Section 3). In this way the detector will be "pointed” in a wrong direction were we expect a fainter shadowing effect.

It is expected that the significance would be around 3σ for small shifts ($\leq 0.1^\circ$), then it would decreases significantly while increasing the shift as we expected. The study is ongoing, but relevant systematic errors are not expected in the absolute pointing of the ANTARES detector.

5. Conclusions

The Moon shadow in the atmospheric muon flux has been observed with the ANTARES neutrino telescope. The optimization of event selection has been performed with a dedicated Monte Carlo simulation and an opportune test statistic function has been defined to evaluate the deficit significance. The 2007-2012 data sample has been then analysed showing a 3.1σ evidence of the effect. The Moon shadow profile has been fitted assuming a Gaussian shape for the detector point spread function, in this way we derived the angular resolution for the atmospheric muon flux: $0.7^\circ \pm 0.2^\circ$.

The results reported in this work are the first Monte Carlo independent measure of the angular resolution and the first study of the pointing systematics of the ANTARES detector exploiting a celestial calibration source.

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PoS(ICRC2015)1138