Search for a correlation between ANTARES neutrinos and Pierre Auger Observatory UHECRs arrival directions

The ANTARES collaboration

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This paper presents a search for correlation in the arrival directions of 2190 neutrino candidate events detected in 2007-2008 by the ANTARES telescope, and 69 ultra-high energy cosmic rays (UHECRs) observed by the Pierre Auger Observatory between January 1st 2004 and December 31st 2009. No significant correlation was found. The corresponding 90% C.L. upper limit on the neutrino flux from each observed UHECR direction (assuming an equal flux from all of them and for E^{-2} energy spectrum) is 4.99×10^{-8}GeVcm^{-2}s^{-1}.

1 Introduction

The astrophysical sources of ultra-high energy cosmic rays (UHECRs) remain unknown. These particles are expected to be of extragalactic origin and potential sites of acceleration include jets of gamma-ray bursts (Waxman 1995; Vietri 1995; Waxman & Bahcall 1997; Murase et al. 2006) or active galactic nuclei (Biermann & Strittmatter 1987; Stecker et al. 1991; Rachen & Biermann 1993; Nellen et al. 1993). The search for UHECR sources is complicated by their deflection in magnetic fields inside and outside of the Galaxy and by the extremely low rates of these particles: above 10^{19}eV, about 1 particle per km^2 per century. Due to their interactions with photons of the cosmic microwave background via the GZK mechanism (Greisen 1966; Zatsepin & Kuzmin 1966), UHECRs propagation distances are limited, for example for protons, to about 100 Mpc. While the existence of a cut-off in the energy spectrum of UHECRs, first observed by the HiRes experiment (Abbasi et al. 2008a, 2009), has now been confirmed by the data of the Pierre Auger Observatory (Abraham et al. 2008a, 2010), the composition of the cosmic rays above a few 10^{18}eV, crucial for estimation of expected magnetic deflection magnitude, remains uncertain. Although data from the Pierre Auger Observatory seem to indicate a transition from light to heavier composition above 40EeV, this trend is still subject to large uncertainties, in particular related to the lack of accurate modeling of hadronic interactions in the relevant energy domain.

A new and promising method to study the origin of the UHECRs is the multimessenger approach, which is based on the detection of secondary fluxes of gamma-rays and neutrinos associated with the decay of pions resulting from the interaction of the UHECRs with matter or photon fields in the vicinity of the cosmic accelerators (Waxman & Bahcall 1999; Bahcall & Waxman 2001; Becker 2008; Becker & Biermann 2009). Although gamma-rays have been linked to astrophysical sources by recent observations (H.E.S.S., MAGIC, VERITAS, Fermi), an unambiguous identification of these sources as sites of hadronic acceleration requires the detection of the associated neutrino flux. Neutrinos, being neutral and weakly interacting particles, are neither deflected nor attenuated during their propagation from the source to the Earth. Their small cross section interaction with matter makes their detection challenging and requires the construction of very large telescopes. The currently operating neutrino telescopes, ANTARES, IceCube and BAIKAL, have not yet observed any statistically significant cosmic neutrino source (Adrián-Martínez et al. 2011; Abbasi et al. 2011; Avrorin et al. 2009).

In this paper, the first source stacking method optimized for a correlation of arrival directions of UHECRs and neutrinos have been developed and applied on the neutrino candidate events detected by the ANTARES telescope and the UHECR events observed by the Pierre Auger Observatory. Would such a correlation be observed, it would indicate regions of the sky where the sources of UHECR and/or neutrinos could plausibly lie, as well as shed light both on the UHECR composition and on the intensity of magnetic fields in and outside of the Galaxy. An observed correlation would also exclude the possibility that the dominant sources of UHECRs are transient sources, since the time delay between neutrinos and protons coming from such a source, is orders of magnitude larger than the observation time of the ANTARES telescope and the Pierre Auger Observatory.

This paper is organized as follows. The discussion about deflection of UHECRs in magnetic fields is presented in Section 2. The data samples are presented in Section 3 and the background and signal simulations are explained in Section 4. The angular search bin optimization and the discovery potential are discussed in Section 5 and the results are given in Section 6.

2 Magnetic deflection of UHECRs

In this paper, ANTARES telescope neutrino candidate events directions were correlated with UHECR events recorded by the Pierre Auger Observatory, using a source stacking method in which the cumulative neutrino signal from all UHECR directions is summed and compared with the expected background. Such an approach is known to be sensitive to a significantly lower flux per source for a 5 σ 50% discovery potential than the single point source approach. A key parameter for the analysis is the angular search cone around each UHECR direction and is mainly determined by the assumed magnetic deflection of the UHECRs.

Protons with the highest energies (above 10^{19}eV) are expected to be deflected by the Galactic magnetic field up to a few degrees (Stanev 1997; Alvarez-Muniz et al. 2002; Takami & Sato 2010). Medina Tanco et al. (1998) calculated that protons with energies of $4{\times}10^{19}$eV should be deflected by about 5°. Harari et al. (1999) concluded that 10^{20}eV protons arrive to Earth almost undeflected. Deflection angles of about 3°, for protons of $4{\times}10^{19}$eV, were estimated by Prouza & Smida (2003). Also, most authors suggested insignificant deflection angles for protons traveling through extragalactic magnetic fields, even for a propagation through galaxy clusters (Dolag et al. 2005; Kotera & Lemoine 2008; Das et al. 2008; Aharonian et al. 2010). However, if the composition of UHECRs is mostly heavy, identification of their sources would be likely impossible. Medina Tanco et al. (1998) found that Fe nuclei with energy of $2.5{\times}10^{20}$eV can be deflected up to 20° in the Galactic magnetic field. Prouza & Smida (2003) also calculated deflection angles of few tens of degrees for heavy UHECRs. This was also confirmed in a recent paper by Takami & Sato (2010).

In order to avoid the trial factor associated with using multiple tolerance windows for the magnetic deflection a single value of 3° is adopted for this analysis.

3 Neutrino and UHECR data

The ANTARES neutrino telescope (Ageron et al. 2011) is located in the Mediterranean Sea, 40 km off the southern coast of France (42° 48′N, 6° 10′E), at a depth of 2475 m. It was completed in 2008 and its final configuration is a three-dimensional array of photomultipliers in glass spheres (optical modules (Amram et al. 2002)), distributed along twelve lines anchored at the sea bottom and kept taut by a buoy at the top. Eleven of these detection lines contain 25 storeys of triplets of optical modules and one contains 20 triplets. The lines are subject to the sea currents and can change shape and orientation. A positioning system based on hydrophones, compasses and tiltmeters is used to monitor the detector geometry with an accuracy of 10 cm. The total instrumented volume of the ANTARES telescope is about 10^7m^3. The detection principle is based on measuring the Cherenkov light emitted in the detector by high energy muons, that result from neutrino interactions inside or near the instrumented volume of the detector. The large background from downgoing muons produced in cosmic ray air showers is reduced by selecting only upgoing muons as neutrino candidates.

The data acquisition system of the detector (Aguilar et al. 2007) is based on the ”all-data-to-shore” concept, in which signals from the photomultipliers above a given threshold are digitized and sent to shore for processing. The absolute time is provided by GPS and the precise timing resolution for the recorded photo-multiplier tube signals, of order 1 ns, is required to maintain the angular resolution of the telescope. The arrival times of the hits are calibrated as described in (Aguilar et al. 2011). A L1 hit is defined either as a high-charge hit, or as hits separated by less than 20 ns in optical modules of the same storey. At least five L1 hits are required throughout the detector within a time window of 2.2 μs, with the relative photon arrival times being compatible with the light coming from a relativistic particle. Independently, events which have L1 hits on two sets of adjacent or next-to-adjacent floors are also selected. The physics events are stored on disk for offline reconstruction.

The data used in this analysis were collected between Jan 31st, 2007 and Dec 30th 2008. During this time the construction of the detector was still in progress. The detector consisted of 5 lines for most of 2007 and of 9, 10 and 12 lines during 2008. For part of that period, the data acquisition was interrupted for the connection of new lines, and in addition, some periods were excluded due to the high bioluminescence-induced optical background. The resulting effective live time of the analysis is 304 days.

These events were reconstructed offline to determine the muon trajectory, using a multi-stage fitting procedure. The final stage of this procedure consists of a maximum likelihood fit of the measured photon arrival times. A quality parameter, indicated by λ, is determined based on the final value of the likelihood function. Selection cut on parameter λ >-5.4 has been optimised in order to have the best point source sensitivity (Adrián-Martínez et al. 2011). The estimated angular error obtained from the muon track fit is required to be smaller than 1°. The final data sample consists of 2190 up-going neutrino candidate events. For this current analysis, no selection was done based on the energy reconstruction. The angular resolution was estimated to be 0.5±0.1°. The simulations indicate that the selected sample contains 60% atmospheric neutrinos, the rest are misreconstructed atmospheric muons.

Previously, the Pierre Auger Observatory reported an anisotropy in the arrival directions of UHECRs (Abraham et al. 2008b) and indicated a correlation with Active Galactic Nuclei (AGN) from Veron-Cetty&Veron (VCV) catalog (Véron-Cetty & Véron 2006). After a scan of the relevant parameters, the prescription was made on a subsample of data and the correlation was found to be the most significant for a sample of 27 events corresponding to cosmic ray energies higher than 57EeV, falling within a bin of size 3.1° around the AGNs from the VCV catalog, located at distances smaller than 75Mpc. However, the HiRes Collaboration reported an absence of a comparable correlation in observations in the Northern hemisphere (Abbasi et al. 2008b). Further, the suggested correlation of the Pierre Auger UHECRs with the nearby AGN sources decreased in the following analysis (Abreu et al. 2010) with 69 events at energies above 55EeV ($10^{19.74}$ eV), observed until 31 December 2009. These 69 UHECR events were used in the correlation analysis presented in this paper.

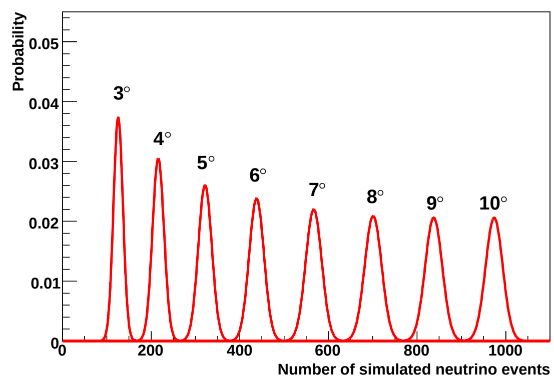

Figure 1: The probability density functions of the number of neutrino events in 3-10° bins centered on 69 UHECR directions.

4 Background and signal simulations

In order to study the statistical significance of any observed correlation between datasets and determine an optimal angular search bin, Monte Carlo (MC) set with 10^6 pseudo-experiments is generated, each with 2190 neutrinos and 69 UHECRs. In each of these pseudo-experiments the positions of UHECRs are fixed according to the Pierre Auger Observatory dataset and the neutrino background is randomly generated by scrambling the 2190 neutrinos from the ANTARES telescope dataset in right ascension. The number of neutrinos within an angular bin of chosen size, centered on 69 UHECR events is counted. The normalized probability density function (PDFs) is calculated and fitted with a Gaussian distribution, to obtain the mean neutrino count and its standard deviation expected from the randomized background samples. This procedure is repeated for a range of different bin sizes.

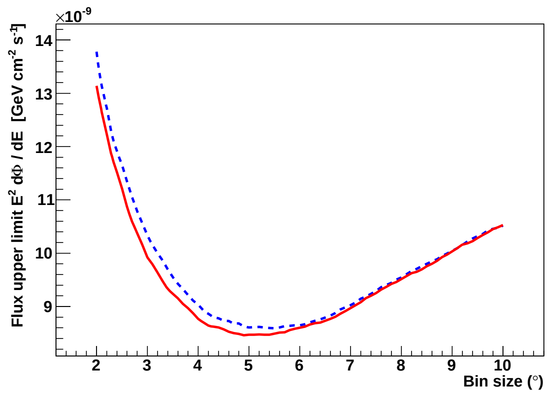

Figure 2: The mean flux upper limit (90% CL) as a function of the search bin size is presented with the red solid line. The mean flux upper limit for two times lower angular resolution is shown with the blue dashed line.

For illustration, Figure 1 shows an example count of neutrinos for bins of 3-10° size. The count of events is done by adding neutrinos in all 69 bins for which the minimum angular distance to UHECRs is smaller than the bin size. In this way, when the same neutrino event falls within multiple bins around the UHECRs, a double counting of neutrino events is avoided. After optimizing an angular bin size (as described in the next Section), the significance of the observed number of neutrino events within 69 bins is calculated by comparison with the distribution for the pure background MC sample.

The signal events are simulated assuming a neutrino energy spectrum proportional to E^{-2} and equal flux strength from each of 69 UHECR directions. Flux values from 0.5×10^{-8}GeVcm^{-2}s^{-1} to 10^{-7}GeVcm^{-2}s^{-1} are considered. The flux is converted into signal event rate per source using the effective area for 5-12 lines and the corresponding live time. For every source, signal neutrinos are generated according to the Poisson distribution with the event rate per source as mean value. For example, a flux value of 10^{-8}GeVcm^{-2}s^{-1}, gives 0.85 signal neutrinos per UHECR source, or about 58 events for all stacked sources. Signal neutrinos are randomly generated according to a Gaussian which is a result of a convolution of the magnetic field tolerance window of 3° and the angular resolution of the ANTARES telescope. The same amount of background neutrinos is removed from a declination band of 10° centered on each UHECR to ensure that every random sky has 2190 events and to keep the neutrino declination distribution profile close to the observed profile.

5 Angular search bin optimization and discovery potential

Monte Carlo predictions are used to calculate the mean upper limit, or Feldman-Cousins sensitivity (Feldman & Cousins 1998; Hill & Rawlins 2003), that would be observed over the set of pseudo-experiments with expected background n_b and no true signal. Over an ensemble of experiments with no true signal, the background n_b will fluctuate to different values with different Poisson probabilities, each one associated with an upper limit μ_{90}. The mean upper limit is the sum of these expected upper limits, weighted by their Poisson probability of occurrence. Over an ensemble of identical experiments, the strongest constraint on the expected signal flux corresponds to a set of cuts that minimizes the model rejection factor (μ_{90}/n_s) and at the same time minimizes the mean flux upper limit that would be obtained over the hypothetical experimental ensemble. The model rejection factor, as well as the optimized bin size, do not depend on a chosen flux value, as both μ_{90} and n_s are proportional to it.

The described Feldman-Cousin's approach with the Rolke extension (Rolke et al. 2005) was used to calculate the mean upper limit on the neutrino flux per source assuming that the neutrino spectrum follows E^{-2}, for a 90% confidence level, from background samples as shown in Figure 2 (red solid line). Using 3° magnetic deflection tolerance value, the angular search bin that minimizes the flux upper limit is 4.9°.

With the angular search bin size optimized and fixed, it is possible to estimate the probability of making a 3 σ

or a 5 σ 90% C.L. discovery given a certain signal flux. First, the neutrino count necessary for a chosen σ level is determined from the background MC samples. Then, the number of pseudo-experiments with signal, that have more neutrinos in 69 optimized bins than the chosen σ level from background only, is counted and this gives a direct measure of the discovery potential for that particular flux. Figure 3 shows the discovery potential for 5σ (red solid line) and 3σ (red long-dashed line) discovery, for an optimized bin size of 4.9°. Around 125 (75) signal events correlated to the 69 UHECRs directions are needed for a 5σ (3σ) discovery in 50% of trials. This counts correspond to flux per source of 2.16×10^{-8} GeV cm^{-2} s^{-1} and 1.29×10^{-8} GeV cm^{-2} s^{-1} respectively.

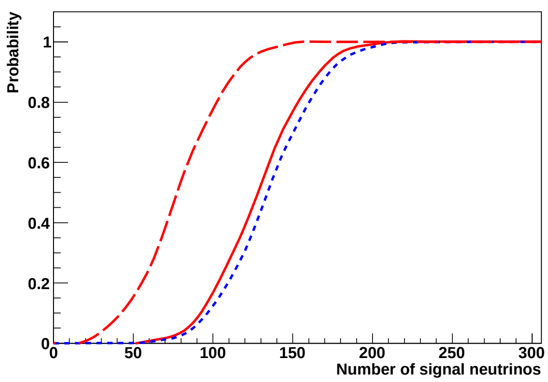

Figure 3: The discovery potential at 3 σ (red long-dashed line) and 5 σ (red solid line) 90% C.L. as a function of the number of neutrino signal events from 69 sources on the whole sky. The discovery potential for two times lower angular resolution is shown with the blue dashed line.

To check the effect of a possible angular resolution systematic error on sensitivity and discovery potential, MC simulations with an angular resolution lowered by a factor of 2 were performed. The optimized bin value in this case is 5.5°, compared with 4.9° obtained from the observed angular resolution. This 100% larger angular resolution results in about 20% higher neutrino flux upper limit. No significant effect is found on the discovery potential. Figures 2 and 3 show respectively optimized bin and discovery potential for observed and 2 times lower angular resolution. Note that the expected error on the angular resolution, as we already mentioned, is estimated to be much smaller (0.1°).

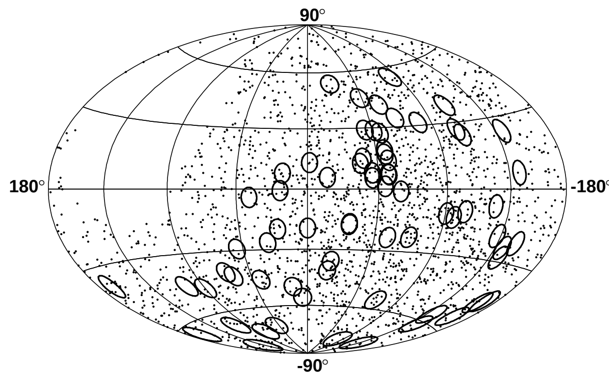

Figure 4: On this skymap in Galactic coordinates, neutrino events are represented with black dots and angular search bins of 4.9° centered on the observed UHECRs with black circles.

6 Results

To analyze the level of correlation between the distribution of 2190 neutrino candidates observed by ANTARES telescope, and 69 UHECRs reported by the Pierre Auger Observatory, neutrino candidate events were unblinded. The significance of an observed correlation is determined with the help of randomized background samples, using the optimized bin of 4.9°. The most probable count for this optimized bin size, or the mean background expectation from the randomized samples, is 310.5 events (in all 69 bins), with the standard deviation of 15.2 events. After unblinding 2190 ANTARES telescope neutrino candidate events, a count of 290 events within 69 bins is obtained (Figure 4), which is sligtly lower than expected. This count is compatible with a underfluctuation of the background, with a significance of 1.4 σ. The corresponding 90% C.L. upper limit on the neutrino flux from each observed UHECR direction (assuming an equal flux from all of them and for E^{-2} energy spectrum) is 4.99×10^{-8}GeVcm^{-2}s^{-1}.

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