PROCEEDINGS OF SCIENCE

Search for a correlation between ANTARES high-energy neutrinos and ultra high-energy cosmic rays detected by the Pierre Auger Observatory and the Telescope Array

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on behalf of the ANTARES Collaboration

A search for angular correlations between high-energy neutrinos detected by ANTARES and the cosmic rays events measured by the Pierre Auger Observatory and the Telescope Array experiments is presented. An unbinned likelihood-ratio method is used, using both the angular information an energy estimation of the reconstructed neutrinos. The search has been applied to the nine-years ANTARES all-flavour point-source sample, leading to a non significant correlation. A 90% upper limit on the flux emitted by the candidate neutrino sources associated to the cosmic ray population is reported: $\Phi^{\rm UL}_{\rm tot} = 1.5\,10^{-7}$ GeV^{-1}cm^{-2}s^{-1}.

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1. Introduction

The connection between ultra-high energy cosmic rays (UHECRs), with energies in the EeV range and high energy neutrinos in the TeV-PeV range can be investigated to understand whether the same astrophysical sources can produce both of them. The observation of such kind of correlation could provide clues to understand the origin of these cosmic messengers. Previous searches that have been performed report only hints of correlations but without the level of significance needed for a discovery [1].

In this search, we use the public data from the Pierre Auger Observatory (PAO) [2] and the Telescope Array (TA) [3] experiments. These two experiments measure UHECRs through the detection of extensive air showers produced in the Earth's atmosphere. They have collected 318 events in total with energies above 52 EeV.

2. ANTARES neutrino events and UHECR data

The ANTARES detector [4] is the largest underwater neutrino telescope in the Northern hemisphere. The ANTARES data-set analyzed here covers a period of time between January 29th, 2007 to December 31st, 2015, for a total of 2423.6 days of live-time. The sample is composed of 7629 track-like (mostly muon neutrinos) and 180 shower-like events (mostly induced by ν_e charged current and by all flavor neutral current ν interactions). The selection procedure of the data has been optimized for point source searches, and is described precisely in [5].

The Pierre Auger Observatory is located near the town of Malargüe in the Mendoza Province, Argentina, at 1400 m above sea level and covers an area of $\sim$ 3000 km^2 which makes it the largest cosmic ray observatory ever constructed. The PAO is a hybrid detector, it consists of a Surface Detector (SD) array of 1600 water-Cherenkov particle detector stations overlooked by 24 air fluorescence telescopes. In addition, three high elevation fluorescence telescopes overlook a surface of 23.5 km^2 where additional 61 water-Cherenkov particle detector stations are installed. The public data set used in the present work, taken from [6], consists of 231 cosmic-ray events with zenith angle $\theta \leq 80^\circ$ and energy $E_{CR} \geq 52$ EeV recorded by the SD from January 1st, 2004 up to March 31st, 2014.

The Telescope Array (TA), situated in Utah, USA, consists of 507 plastic scintillator detectors, each of 3m^2, located on a 1.2 km square grid, covering an area of $\sim$700 km^2 [3]. The detector has been fully operational since March 2008. For this analysis, we use the 87 events collected between May 11th, 2008 and May 4th, 2014.

It should be noted that the absolute energy scale of UHECRs may contain a systematic error which may be, in principle, different for the two experiments. According to the results of the specific investigations of the TA-Auger Energy Spectrum working group [7], the UHECR spectra measured by TA and Auger could be made coincident in the region around 10^{19}eV (the ankle region) by down-shifting the TA energies by $\sim$ 13% or equivalently by up-shifting the Auger energies. A down-shift of the TA energies by 13% has been chosen for this analysis.

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3. Description of the analysis

3.1 Magnetic deflection of UHECRs

Cosmic rays, unlike neutrinos, are deflected by magnetic fields (galactic and extra-galactic) during their propagation, the magnitude of the deflection being inversely proportional to their magnetic rigidity $R = pc/Ze \simeq E/Ze$. Unfortunately, the chemical composition of UHECRs is not yet reliably measured at the highest energies in consideration here [8][9], essentially due to lack of statistic available in the fluorescence data that has a smaller duty cycle than surface arrays. This situation could change in the next few years when the upgrade of the Pierre Auger Observatory (AugerPrime) [10] will be fully operational.

The cosmic magnetic fields that deflects cosmic rays are separated into a galactic and an extra-galactic contribution, both being poorly known. The galactic field has a magnitude of the order of μG, containing both a coherent component following the spiral structure of the gas and stellar population, and a turbulent component.

Extragalactic magnetic fields, which are even less known, should provide a sub-dominant contribution for nearby CR sources (closer than several hundreds of Mpc), upper limits on the average field being of the order of $1nG$ [11]. Among the recent models of the galactic magnetic field [12] [13], the average deflections predicted are comparable in magnitude, but show very different patterns on the sky, making reliable predictions difficult.

In the following analysis, we use the median deflection angle that is predicted by those models for protons, assuming only a gaussian deflection around the position of the observed UHECRs. Hence for each UHECR we parametrize the individual magnetic deflection as:

$$\sigma_B(E_j^{CR}) = 3^\circ \times \frac{100}{E_j^{CR}(EeV)}. \tag{3.1}$$

3.2 Statistical method

The method uses an unbinned maximum-likelihood approach, where the cosmic rays are considered as tracers of candidate neutrino sources. The search compares the null hypothesis H_0: the neutrinos detected by ANTARES come from atmospheric background, with an alternative hypothesis H_1: a fraction of the detected neutrinos are emitted with a common spectral index γ from astrophysical point sources located around the position of UHECRs in the sky.

We assume that there is an underlying neutrino source associated to each cosmic ray, injecting the same flux $\Phi = \Phi_0\,(\mathrm{E}/1\,\mathrm{GeV})^{-\gamma}$, where the normalization Φ_0 is expressed as a flux per flavor (accounting for both ν and $\overline{\nu}$'s), in units of $\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. However, as we test the correlation between ν's and the stacking of $\mathrm{N_{CR}}$ cosmic ray positions, the relevant quantity in the following analysis will be the total flux injected $\Phi_{\mathrm{tot}} = \mathrm{N_{CR}}\,\Phi$.

The conversion from the flux Φ injected by a point source at a given declination and the corresponding number of signal events n_s detected is given by the acceptance of the ANTARES detector.

The acceptance is computed in bins of declination and spectral indexes, using Monte-Carlo simulations where the same set of cuts than for data are applied. For example, in this analysis, the average number of signal events expected for a total injected flux $\Phi_{\rm tot} = 10^{-8}\,({\rm E}/1\,{\rm GeV})^{-2}\,{\rm GeV}^{-1}{\rm cm}^{-2}{\rm s}^{-1}$ is $\simeq 2$ tracks and $\simeq 0.5$ showers.

Each neutrino event is characterized by its reconstructed direction (α_i, δ_i) in equatorial coordinates and its energy through the number of hits Nh_i used in the reconstruction procedure. For one particular channel (tracks or showers), the log-likelihood for the hypothesis H_1 can be written as:

$$LL(\text{data}|H_1) = \sum_{i=1}^{N} \log \left[\frac{n_s}{N} S_\gamma(\alpha_i, \delta_i, Nh_i) + \left(1 - \frac{n_s}{N}\right) B(\delta_i, Nh_i) \right] \tag{3.2}$$

where N is the total number of ν events detected in the considered channel, the function S_γ is the probability density function (PDF) describing the expected astrophysical signal and the function B represents the background PDF, both function being normalized to unity. The free parameters are: n_s the number of signal events and the spectral index γ of the neutrino sources.

The log-liklihood for the background only hypothesis H_0 is simply:

$$LL(\text{data}|H_0) = \sum_{i=1}^{N} \log\, B(\delta_i, Nh_i) \tag{3.3}$$

The test statistic that is used to compare the two hypothesis is the log-likelihood ratio:

$$Q = LL(\text{data}|H_1)^{max} - LL(\text{data}|H_0) \tag{3.4}$$

using the values of the parameters $(\tilde{n}_s, \tilde{\gamma})$ that maximize the likelihood under hypothesis H_1.

We use pseudo-experiments to compute the test statistic distribution under the H_0 hypothesis, that will be used to estimate the significance of the result. The discovery potential of the method can be estimated by generating pseudo-experiments where a neutrino flux Φ is injected for a given spectral index γ.

The combination of the track and shower channels is performed using a global log-likelihood function:

$$LL(\text{data}|\mathrm{H}_1) = \sum^{\mathrm{N_{tracks}}} \log \left[\frac{n_{\rm tr}}{\mathrm{N_t}} S_\gamma^{\rm tr} + (1 - \frac{n_{\rm tr}}{\mathrm{N_t}}) B^{\rm tr} \right] + \sum^{\mathrm{N_{showers}}} \log \left[\frac{n_{\rm sh}}{\mathrm{N_s}} S_\gamma^{\rm sh} + (1 - \frac{n_{\rm sh}}{\mathrm{N_s}}) B^{\rm sh} \right]$$

where the free parameters are the number of signal track events $n_{\rm tr}$, the number of shower events $n_{\rm sh}$ and the common spectral index γ.

3.3 Ingredients for the likelihood

The signal PDF $S(\alpha, \delta, Nh)$ represents the probability for an astrophysical neutrino emitted with energy E from a source located in (α_s, δ_s), to be detected and reconstructed by ANTARES

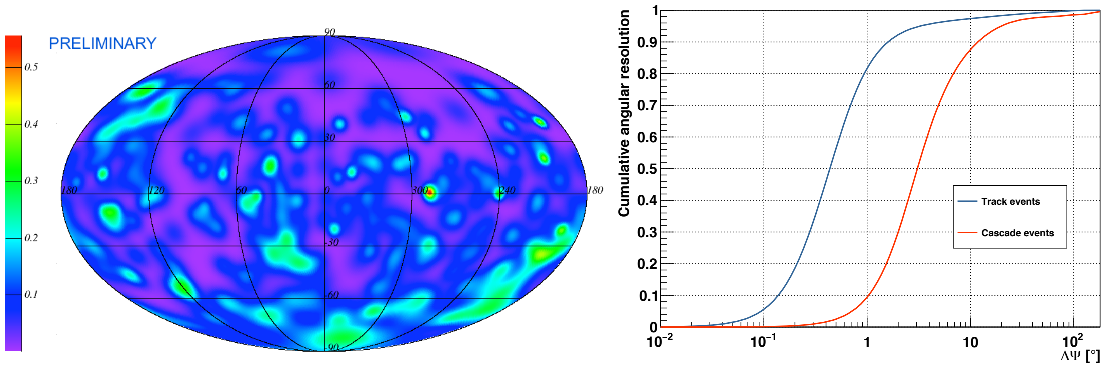

Figure 1: Left: map in equatorial coordinates of the source term f_{CR}, representing the probability to find a neutrino source in a given direction. The intensity of the color scale reflects only the contrast of the map, as the integral of the source term over the solid angle is made equal to 1. **Right**: average Point Spread Function for an E^{-2} spectrum: the cumulative distribution of the angle between the reconstructed direction of track (blue) and shower (red) events and the true Monte-Carlo neutrino direction is shown.

with $(\alpha_{rec}, \delta_{rec}, Nh_{rec})$. The signal PDF is built as a product of two terms: an angular, and an energy dependent term:

$$S_{\gamma}(\alpha, \delta, Nh) = f_{\gamma}(\alpha, \delta) \times g_{\gamma}(Nh) \tag{3.5}$$

The angular term $f_{\gamma}(\alpha, \delta)$, is defined as:

$$f_{\gamma}(\alpha, \delta) = A_{\gamma}(\delta) \times (f_{\mathrm{CR}} * \mathrm{PSF}_{\gamma})(\alpha, \delta) \tag{3.6}$$

where A_{γ} is the ANTARES acceptance, $f_{CR}(\alpha_s, \delta_s)$ represents the probability for a neutrino source associated to a cosmic ray to be located at (α_s, δ_s). Finally, to obtain the probability of reconstructing a neutrino at $(\alpha_{rec}, \delta_{rec})$, this source term is convoluted with the Point Spread Function (PSF) of the considered channel (right of figure 1). The acceptance and the PSF are tabulated as a function of declination and spectral index γ.

The source term f_{CR} is obtained by applying an energy dependent gaussian smearing $\sigma(E)$ over the position of cosmic rays:

$$f_{CR}(\alpha_i, \delta_i) = \sum_{j=1}^{N_{CR}} \frac{\Phi}{2\pi\sigma_j^2} \exp\left(-\frac{d_{ij}^2}{2\sigma_j^2}\right) \tag{3.7}$$

where d_{ij} is the angular distance between the position of the neutrino and the cosmic ray. The standard deviation $\sigma_j(E) = \sqrt{(\sigma^2_{Auger/TA} + \sigma^2_B(E_j^{CR}))}$, is obtained by summing in quadrature the angular resolution of the cosmic rays experiments: $\sigma_{\mathrm{Auger}} = 0.9°$ [6] and $\sigma_{\mathrm{TA}} = 1.5°$ [14], with the magnetic deflection term $\sigma_B(E)$ given by equation 3.1. The function f_{CR} is represented in equatorial coordinates on figure 1 (left).

The energy term $g_{\gamma}(Nh)$ uses the number of hits information to better discriminate atmospheric neutrinos and muons from the candidate astrophysical signal, due to their very different spectrum

($\Phi_{\text{atm}} \propto E^{-3.7}$). The figure 2 shows for track and shower channels the expected distribution of the number of hits for the atmospheric background and for an E^{-2} astrophysical flux, together with the values observed in the real data sample.

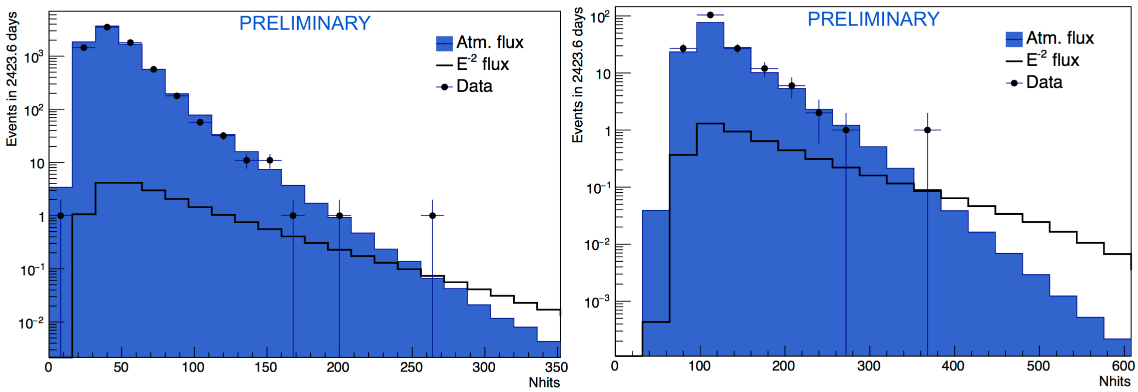

Figure 2: Distributions of the number of hits in the track (left) and shower (right) channels. The expectation for the atmospheric background (blue histogram) and for a diffuse astrophysical $\Phi_0 E^{-2}$ flux (black line) are represented, together with the data (black dots). The vertical scale indicates the number of events expected for the total live time considered in the analysis, the normalization of the diffuse flux used for comparison is $\Phi_0 = 10^{-8}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1}.

The background PDF $B(\delta, Nh)$ that accounts for the atmospheric flux is assumed to be uniform in right ascension. As for the signal PDF, it is factorized into an angular term and an energy term:

$$B(\delta, Nh) = f(\delta) \times g(Nh) \tag{3.8}$$

where $f(\delta)$ is the declination distribution and $g(Nh)$ is the distribution of the number of hits shown in figure 2. The expected contribution of an astrophysical signal being small, the actual declination distribution observed in data is used for the function $f(\delta)$ (see figure 3), whereas the function $g(Nh)$ is obtained from Monte-Carlo. To get a stable behavior of the minimization procedure, a smooth function fitted on the declination distribution is effectively used in the likelihood.

3.4 Discovery Potential

To evaluate the sensitivity of the analysis, a large number of pseudo-experiments have been generated for the background and signal. Background events are simulated by sampling directly the declination and the number of hits from the parameterization of B, while the right ascension is sampled from a uniform distribution in $[0; 2\pi]$.

The signal events are generated for a given flux Φ_0 per source with the following procedure: for each cosmic ray, a random neutrino source position is determined from a 2d gaussian function corresponding to equation 3.7. A random number of neutrino events is then generated according to a Poisson distribution with a mean equal to $\Phi_0 \times A_\gamma(\delta)$. The final coordinates of the events are obtained by adding a random deviation sampled from the $\text{PSF}_\gamma(\delta)$, and a number of hits from the histograms of figure 2.

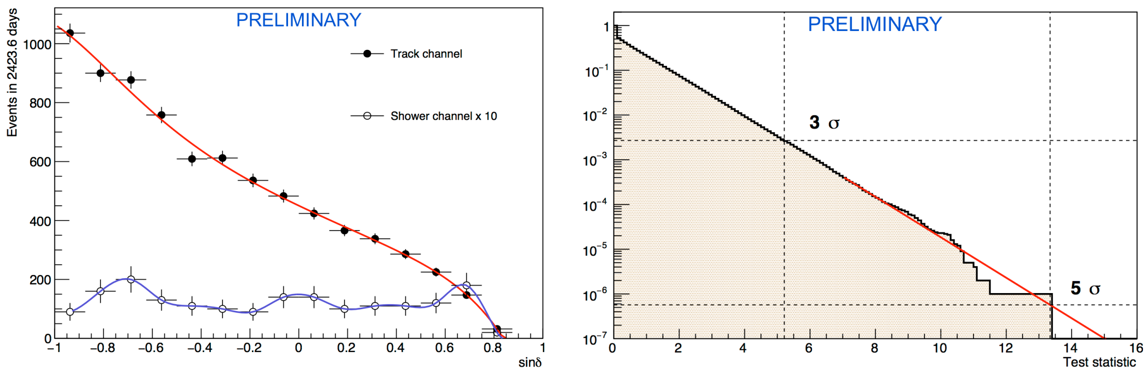

Figure 3: **Left** : Declination distribution observed in data in the track (black dots) and shower (empty circles) channels, together with the smooth curves that are used to compute the background PDF for the likelihood (for presentation purposes, the shower channel is multiplied by a factor 10). **Right**: Anti-cumulative distribution of the test statistic $Q = LL(\text{data}|H_1)^{max} - LL(\text{data}|H_0)$ in the background only hypothesis, for the combined sample tracks+showers. The dotted lines show the 3σ and 5σ significance levels and the corresponding values of the test statistic. An exponential fit (red line) is performed on the tail of the distribution to estimate the position of the 5σ level.

The distribution of the test statistic for the combined sample in the background only hypothesis is shown in figure 3. It is obtained by performing the full minimization procedure on a large number (10^6) of pseudo-experiments. The value of the test statistic $Q_{3\sigma}$ and $Q_{5\sigma}$ corresponding to p-values of 2.7×10^{-3} and 5.7×10^{-7} are reported for illustration.

The median discovery potential at 3 or 5σ is defined as the minimum flux $\Phi_{3/5\sigma}$ (or number of events $n_{3/5\sigma}$) that is required to get a test statistic value $Q > Q_{3/5\sigma}$ in 50% of the pseudo-experiments. The table 1 summarizes the results that have been obtained for an E^{-2} spectrum.

Discovery potential	$n_{3\sigma}$	$n_{5\sigma}$	$\Phi^{tot}_{3\sigma}$ ($\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$)	$\Phi^{tot}_{5\sigma}$ ($\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$)
Tracks	64	117	$3.1\,10^{-7}$	5.710^{-7}
Showers	21	40	$4.4\,10^{-7}$	$8.3\,10^{-7}$
Combined	51 tr +12 sh	94tr + 22 sh	$2.5\,10^{-7}$	$4.6\,10^{-7}$

Table 1: Discovery potential of the analysis for tracks (tr) showers (sh) and for the combined sample.

4. Results and conclusion

The application of the likelihood fit on the full data sample tracks+showers gives the following results: $n_{\text{tr}} = 10^{-3}$, $n_{\text{sh}} = 11.4$, with a spectral index $\gamma = -3$. The test statistic is $Q_{\text{data}} = 0.26$, leading to a p-value of $p = 0.46$ (computed from the curve of figure 3).

From this non-significant result, we can compute the 90%C.L upper-limit on the total all-flavor flux Φ_{tot} that is emitted by the potential neutrino sources associated with the UHECRs population. We estimate with pseudo-experiments the smallest flux that is required to get at least

90% of the test statistics values $Q > Q_{\rm data}$, leading to a value: $\Phi^{\rm UL}_{\rm tot} = 1.5\,10^{-7}$ GeV^{-1}cm^{-2}s^{-1}. For comparison with other analyses, this limit can be converted into an equivalent diffuse flux of $\Phi_{\rm dif} = \Phi^{\rm UL}_{\rm tot}/4\pi = 1.2\,10^{-8}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1}.

The neutrinos from the all-flavors point source sample collected by ANTARES during nine years of data acquisition shows no evidence of correlation with the 318 UHECRs above 52 EeV measured by the Pierre Auger Observatory and the the Telescope Array.

We note that the observation of such a correlation relies on several assumptions that may not be fulfilled: the magnetic deflections that we assume could be largely underestimated, especially if the cosmic ray mass composition is heavy.

The potential strong difference in range between the UHECRs above ~ 50 EeV that suffer from energy losses and the neutrinos that can come from cosmological distances reduces the amount of common sources that can be observed. The propagation time of cosmic rays in magnetic fields compared to neutrinos could also lead to the absence of correlation if the UHECRs sources are transient.

In addition, the energies of the cosmic rays considered here are ~ 6 orders of magnitude higher than those of the neutrinos, hence only a fraction of the neutrinos sources could potentially be the same accelerators of UHECRs.

The discovery potential of future searches will be enhanced with more statistic and when a measure of the mass composition of the cosmic rays at the highest energies will be available.

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