Search for correlations between high-energy gamma rays and neutrinos with the HAWC and ANTARES detectors

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ANTARES is an underwater neutrino detector in the Mediterranean Sea. Its location, reconstruction accuracy for all-flavor neutrino interactions, and low energy threshold, make it the most sensitive neutrino observatory for searches below 100 TeV over large parts of the sky. The HAWC experiment is a water Cherenkov gamma-ray detector located in Mexico. Thanks to its large field of view it is an excellent instrument to observe the very-high energy gamma-ray sky and perform high-sensitivity surveys of the Galactic Plane. The 10-year ANTARES data set and 3-year HAWC point source surveys are used to search for all-flavor neutrino emission in correlation with the highly-significant observations by HAWC in the gamma-ray sky by means of a maximum-likelihood template search. No significant observation for a correlation has been identified and upper limits on the neutrino flux from the HAWC observations have been set.

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1. Introduction

The search for the origin of Galactic Cosmic Rays (GCRs) led to consider most of the sources located in the Galactic Plane responsible for the acceleration of GCRs up to PeV energies. The very-high-energy observations of these point-like sources give us the possibility to study GCR accelerators and the mechanisms responsible for their acceleration.

The interaction of the hadronic component of GCRs with the dense inter-stellar medium (ISM), either close to the sources or while they diffuse through the Galactic Plane (GP), is expected to produce high-energy photons and neutrinos via the decay chains of neutral and charged mesons, carring roughly 5 and 10% of the primary CRs energy, respectively [5]. GCRs around the *knee* of the energy spectrum would thus produce neutrinos and photons mostly at energies of about 10–100 TeV [6]. On the other hand, the interaction of the leptonic component of primary CRs are expected to produce only photons via radiative energy loss processes.

Multi-messenger searches combining gamma-ray and neutrino observations are necessary for the better understanding of Galactic accelerators. In order to disentangle the hadronic and leptonic scenarios, and enhance the identification of an individual Cosmic Rays (CR) accelerator, the association between high-energy neutrinos[1] and high-energy gamma-rays should be investigated.

Surveys of GP gamma-ray emitters are available from data collected by the H.E.S.S. (High Energy Stereoscopic System)[7] and HAWC (High-Altitude Water Cherenkov) Observatory [9, 11, 12]. Supernova Remnants (SNRs) and Pulsar Wind Nebula (PWNe) constitute the majority of identified sources, even though a large quantity of high-energy emission has not yet been classified as belonging to a specific class of objects. The H.E.S.S. high-energy observation of the very central part of our Galaxy suggests the presence of PeV CRs interacting with the local medium [14].

Both the ANTARES [15] and IceCube [16] Collaborations put upper limits on neutrino emissions from point-like and extended sources in the central part of the GP, with the best results coming from the combination of the data samples collected by both experiments [17] – no significant excess of cosmic events above the atmospheric foregrounds is observed. Similarly, searches are conducted aiming at the identification of the diffuse component produced by GCR interaction with the ISM, both by ANTARES [18, 19] and IceCube [20] and a combination of their data samples [21]. Moreover no Galactic neutrino emitter or emission region is identified.

In this work, data collected with the ANTARES neutrino telescope and with the HAWC observatory are used to probe a possible correlation between high-energy gamma-rays and neutrinos.

2. The ANTARES and HAWC detectors

The HAWC observatory [23] is a high-energy gamma-ray detector, located at an altitude of 4100 meters above sea level, on the flanks of the Sierra Negra volcano near Puebla, Mexico. The detector is composed of 300 cylindrical water tanks, 4.5 meter high and 7.3 meter in diameter [24]. Each tank is equipped with four photomultiplier tubes (PMTs), the central one is 10 inches, while the 3 pheripheral are 8 inches, located at the bottom of the tank. The PMTs collect the Cherenkov light induced in the water contained in the tank by particles produced by the interaction of gamma-rays and CRs in the atmosphere [27, 28].

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[1]Here and in the following, the word *neutrino* refers to both ν and $\bar{\nu}$ unless otherwise specified.

The HAWC configuration allows the detector to be sensitive to gamma-rays in the energy range between ~300 GeV up to a few hundred TeV, and to reach an angular resolution between 0.1 and 1 degree. The full detector has been operational since March 2015, continuously observing the sky with an instantaneous field of view of 15% of the sky and covering daily two thirds of the sky, with high duty cycle within the declination range from −26° to 64°.

The ANTARES telescope [25] is an underwater neutrino detector - anchored to the seabed at a depth of about 2500 metres, off-shore the southern coast of France. The detector consists of a three-dimensional array of 885 optical modules (OMs) distributed over 12 450-m long vertical strings and arranged on a 140-m wide footprint, with a instrumented volume of 0.02 km^3. Each OM is a pressure-resistant glass sphere hosting a 10-inch PMT.

Detector operations began in 2007 and the apparatus is taking data continuously in its full configuration since 2008. With an instantaneous field-of-view of more than 2π – by observing upward-going particles passing through the Earth from below the detector – the detector allows for almost complete daily coverage of the sky at energies between 100 GeV and 1 PeV, with a median angular resolution of the order of 0.4° [29].

3. Data analysis

In the analysis presented here, the data samples collected by the HAWC Observatory while performing two sky surveys for the search for point sources are used. The first sample, named *sample A*, consists of data collected from November 2014 to June 2019 [11] in the energy range between 300 GeV up to few hundred TeV. A second sample, hereinafter referred to as *sample B*, comprises events with a measured shower energy above a threshold of 56 TeV collected from June 2015 to June 2019. As a result of the HAWC analysis of such data samples, sky-maps providing the value of the differential gamma-ray fluxes in each point of the sky are obtained under a point-source emission hypothesis and following the assumption that the energy spectrum of the gamma-ray emission is described by an unbroken power-law $d\Phi/dE \propto E^{-\Gamma}$ with a fixed spectral index Γ and pivot energy of 7 TeV. For *sample A*, whose energy spectrum covers the full energy range of sensitivity of the HAWC detector, a spectral index $\Gamma = 2.5$ is assumed, while for *sample B*, consisting of only high energy events, a harder spectrum with $\Gamma = 2.0$ is considered, as in [12]. The significance of the detection of gamma-ray sources is then given as the sky-map of square root of the test statistic ($\sqrt{TS}$ in the following) of the point-source searches.

To reduce the contribution of unresolved sources and prevent the overestimation of the possible neutrino flux, in the analysis presented here a highly-significant observation of gamma-ray sources is required. In order to achieve such condition a $\sqrt{TS}$ cut corresponding to a 3σ Gaussian significance is applied on the test statistic sky-maps of both *sample A* and *sample B*. In addition to this, the declination range of the search is restricted to $[-20°, 60°]$ in order to remove sky regions to which the HAWC detector is less sensitive. Figure 1 shows the sky maps of the differential gamma-ray flux, in galactic coordinates, of the two data samples. For *sample B* a zoom of the galactic plane region with galactic latitude $b \in [-3°, 3°]$ is shown.

The ANTARES data sample acquired between February 2007 and December 2017 is used in this work, following the same event selection as in the ANTARES point-source search described in [29]. Track-like events (*tr*), induced by charged current muon neutrino interactions [30], and shower-
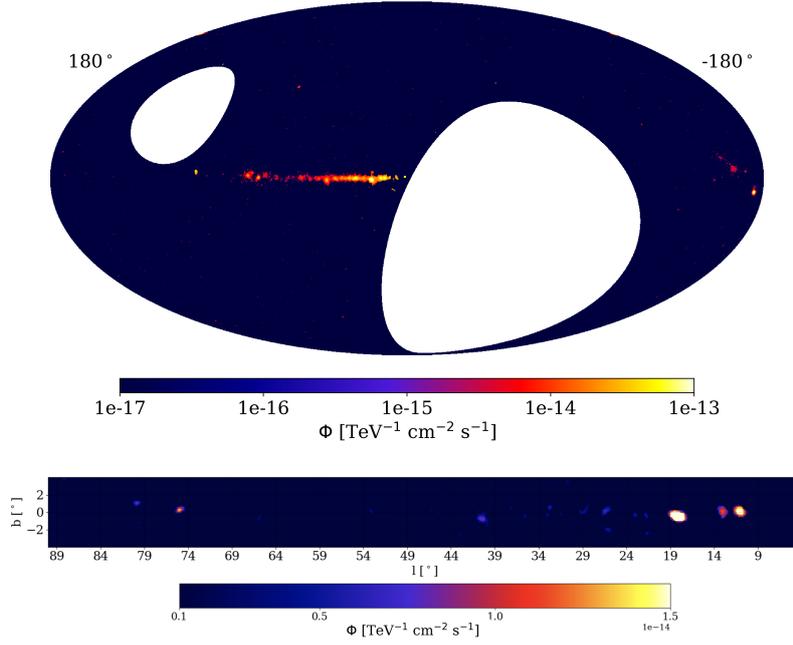
Figure 1: Sky-maps of the HAWC differential flux, for *sample A* (upper panel) and *sample B* (lower panel). The maps are obtained applying a cut corresponding to 3σ on the value of the square root of the HAWC test statistic distributions. The maps are reported in the galactic coordinate reference system.

like events (*sh*), produced by all neutrino flavours and all interaction channels [31], are selected. The background given by downward-going atmospheric muons arriving at large depths is largely reduced by means of selection cuts based on the quality parameters provided by the reconstruction algorithms. According to Monte Carlo (MC) simulations [32], a residual contamination from background of 10% of the sample survives the cuts.

The HAWC sky-maps obtained from *sample A* and *B* are used as spatial and energy templates for a likelihood-based search for astrophysical neutrino candidates in the ANTARES sample. In particular, the same analysis strategy followed in the ANTARES search for Galactic diffuse neutrino flux [19] is applied. The neutrino flux is evaluated from the observed gamma-ray spectrum detected by HAWC according to the model and the assumptions of *Villante and Vissani* [22], and considering equipartition between the three neutrino flavours as expected from standard neutrino emission scenarios and neutrino oscillations over cosmic distances [6].

To evaluate the significance of the association between gamma-rays and cosmic neutrinos in the ANTARES data sample dominated by atmospheric events, a test statistic Q is built as:

$$Q = \log \mathcal{L}_{\text{sig + bkg}} - \log \mathcal{L}_{\text{bkg}} \tag{1}$$

The likelihood function $\mathcal{L}_{\text{sig+bkg}}$ is defined as follows:

$$\mathcal{L}_{\text{sig+bkg}} = \prod_{evt \in \{tr,sh\}} \prod_{i \in evt} \left[\mu_{\text{sig}}^{evt} \cdot pdf_{\text{sig}}^{evt}(E_i, \alpha_i, \delta_i) + \mu_{\text{bkg}}^{evt} \cdot pdf_{\text{bkg}}^{evt}(E_i, \delta_i) \right] \tag{2}$$

where product sequences are over the event topology *evt* (track-like and shower-like neutrino events) and over each event i belonging to the sample *evt*. The E_i is the reconstructed energy, α_i and δ_i

are the right ascension and declination of the event. The μ_{sig}^{evt} parameter is the number of signal events which maximizes the likelihood function while μ_{bkg}^{evt} is the number of background events in the sample.

The signal and background probability density functions (PDFs), pdf_{sig}^{evt} and pdf_{bkg}^{evt}, are defined as the product of two contributions: a spatial component, which encloses the information of the arrival direction of the ANTARES neutrino events, and an energy term describing the expected energy spectrum of the signal and background components.

For the signal, the spatial term depends on the equatorial coordinates of the events (α_i, δ_i). It is given by the expected arrival direction of the reconstructed neutrino events produced in a dedicated MC simulation of the ANTARES response. In the case of background the PDF is derived by computing spline-fits of the δ_i distribution of selected neutrino data set, which allows even to account for possible statistical fluctuations in the event sample.

Both for signal and background, the energy term accounts for the energy spectrum of the reference model used to describe the spectral features of the event sample. In the case of signal the energy spectra of the reference model of neutrino signal is used. While for the background the *Honda et al.* model [33] is considered. The energy term is then built as the distribution of the energy estimator of reconstructed events as a function of the reconstructed declination of the event, obtained in the full MC simulation of the detector.

The test statistic Q distributions are then built by means of pseudo-experiments (PE). A total of 10^3 pseudo-experiments are performed, in which the search method is applied to pseudo data-sets by varying the number of signal events $\mu_{\mathrm{sig}}^{evt} = \mu_{\mathrm{sig}}^{tr} + \mu_{\mathrm{sig}}^{sh}$ injected in the neutrino sample, from 0 up to 30 with 1 event step, and randomly scrambling the background events. The probability density functions of Q, $pdf(Q)$, are then used to estimate the median sensitivity at 90% confidence level (c.l.). The statistical and systematical uncertainties due to the detector response is here treated as in [29]. Example of the $pdf(Q)$ distributions are reported in the left panel of Figure 2.

4. Results and conclusions

The search method based on the maximum likelihood approach described above is used to compute the best-fit value for the number of signal events $\mu_{\mathrm{sig}}^{tr+sh}$ in the ANTARES unscrambled data set. In order to estimate the significance of the observation a p-value is computed by comparing the obtained value of the test statistic, Q_{obs}, with the distribution of Q for the background-only hypothesis obtained from scrambled pseudo data-sets. The p-value is then represented by the percentage of the PEs with a value of the test statistic Q higher than Q_{obs}. Finally, following the same approach described in [35], the 90% c.l. upper limit (u.l.) on the maximal number of signal events (*tr+sh*) $\mu_{\mathrm{sig}}^{u.l.}$ is obtained.

The corresponding upper limit on the number of signal events, $n_{\mathrm{sig}}^{u.l.}$, and the ratio to the number of signal events n_{sig}^0 expected from the assumed model of neutrino emission is reported in Table 1 both for *sample A* and *sample B*, together with the energy range of validity of these limits, computed as the region of the signal neutrino spectrum where the central 90% of events would be visible in ANTARES.

The u.l. on the number of events are translated into differential flux limits, $\Phi_\nu^{u.l.}$, being $\Phi_\nu^{u.l.} = n_{\mathrm{sig}}^{u.l.} / n_{\mathrm{sig}}^0 \cdot \Phi_\nu^{A,B}$, where $\Phi_\nu^{A,B}$ is the cumulative differential neutrino flux averaged over the solid

HAWC Sky-map	μ_{sig}^{tr}	μ_{sig}^{sh}	p-value	$n_{\mathrm{sig}}^{\mathrm{u.l.}}$	n_{sig}^{0}	$\dfrac{n_{\mathrm{sig}}^{\mathrm{u.l.}}}{n_{\mathrm{sig}}^{0}}$	ΔE [TeV]
sample A	6.4	0	0.18	9.6	1.5	6.5	0.45 - 56.2
sample B	0	0	0.33	5.0	1.0	4.9	1.78 - 89.1

Table 1: A summary of the analysis results is reported. For each of the HAWC sky-map the fitted number of signal tracks and showers, the corresponding p-value, the u.l. at 90 c.l. on the number of signal events, the expected signal from the model described in the text, as well as their ratio are shown. In the last column the energy range containing the 90% of reconstructed signal event is also indicated.
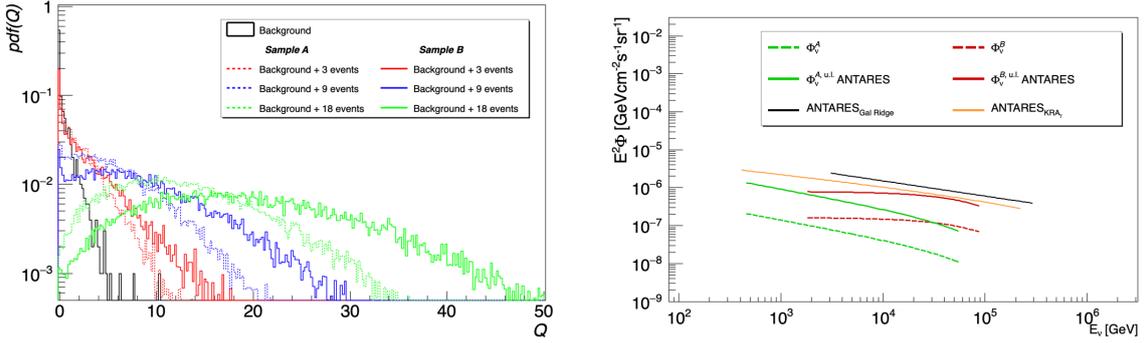
Figure 2: In the left panel the distributions of the probability density function $pdf(Q)$ of the test statistic for the background-only case, and for $\mu_{\mathrm{sig}} = 3$, 9 and 18 for *sample A* and *sample B* are shown. In the right panel the differential flux upper limits for *sample A* (green solid line) and for *sample B* (red solid line) are shown. These limits are compared to the expectations (green/red dashed lines) with the models used in these analyses and with previous ANTARES results in the same area of the sky [18, 19].

angle covered by *sample* A and *sample* B. In the right panel of Figure 2 the u.l. on differential fluxes are compared to the reference neutrino signal assumed in this analysis, derived from the gamma-ray spectrum of the HAWC point-source sky maps according to [22], and with previous ANTARES results obtained from dedicated diffuse Galactic emission searches in the same area of the sky [18, 19].

The ANTARES result from this work is compatible with a non-observation of neutrino emissions spatially coincident with the HAWC signal, expected in case of hadronic production of gamma-rays. This results is valid for both the two different spectral assumptions of the HAWC gamma-ray flux. The sensitivity of ANTARES is still a factor ~ 5 (refer to Table 1) above the neutrino prediction computed from the gamma-ray flux with the two spectral assumptions and the upper limits derives from this search are compatible with what could be expected from the sensitivity level of the analyzed neutrino data-set.

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