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An updated survey of Active Galaxies with the HAWC gamma-ray observatory

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We present an update of the survey of Active Galaxies with the High Altitude Water Cherenkov (HAWC) gamma-ray observatory. This work adds 567 days of HAWC data to the previously published survey, providing a refined analysis of an updated total exposure of 2090 days. The sample includes 138 nearby AGNs from the 3FHL catalog. We fit a modified power-law to their very high energy spectra, including the exponential attenuation caused by the Extragalactic Background Light. We found four sources with significant detections (above 5σ): the radio galaxy M87 and the BL Lac objects Mkn 421, Mkn 501 and 1ES 1215+303. We also report eight sources with a marginal detection (between 3σ and 5σ) of which seven are classified as BL Lac objects and one as a radio galaxy.

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1. Introduction

Active Galactic Nuclei (AGN) are luminous extragalactic sources powered by accreting supermassive black holes hosted in the center of galaxies [1]. Some of them present collimated emission in form of relativistic jets [2], which may extend up to Mpc scales reaching the intergalactic medium out of their host galaxies. Two subclases of jetted AGNs, blazars and radio galaxies, constitute the most common extragalactic gamma-ray sources [3]. This gamma-ray emission is produced by non-thermal processes in the relativistic jet and its apparent luminosity is enhanced by Doppler boosting [4].

Gamma-ray emission from extragalactic sources is heavily attenuated by photon-photon interaction with the Extragalactic Background Light (EBL)[5, 6], which is a diffuse emission constituted by all the electromagnetic radiation emitted by galaxies in the history of the Universe. This attenuation increases for the most distant sources, as well as for the the highest energies.

The High Altitude Water Cherenkov (HAWC) is a gamma-ray observatory, which has been in almost continuous operations (> 95% duty cycle) since 2014. It is located at an altitude of 4100 m in the state of Puebla, Mexico, in the area of the Volcán Sierra Negra mountain. The array consists of 300 Water Cherenkov Detectors (WCD) and is able to study gamma-rays in a wide energy range ($\sim 0.1 - 100$ TeV). However, due to the EBL attenuation, most of AGNs can only be studied at the lowest TeV energies.

In a recently published survey of AGNs [7], 1523 days of HAWC data were analyzed looking for evidence of gamma-ray emission from a sample of 138 nearby ($z < 0.3$) active galaxies, which were selected from the Third Catalog of Hard Fermi-LAT sources (3FHL) [8]. In that work, we found five sources with a significance above 3σ, the BL Lac objects Mrk 421 (65σ), Mrk 501 (17σ), 1ES 1215+303 (3.6σ) and VER J0521+211 (3.2σ), in addition to the radio galaxy M87 (3.6σ).

2. Data and Methodology

We considered the exact same sample of 138 nearby ($z < 0.3$) AGNs as in the previous HAWC survey of active galaxies [7]. However, the current data set consists of 2090 days covering from 2014 November 26 to 2021 January 14. This represents an increase of 37.2% in time with respect to the previous study.

As we did in the previous work, we fit the following spectral model to the whole AGN sample:

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{obs} = K\left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\alpha} e^{-\tau(E,z)}, \tag{1}$$

fixing the spectral index $\alpha = 2.5$ and fitting only the normalization (K). The exponential term accounts for the attenuation produced by the photon-photon interactions with the EBL, which

Detections ($> 5\sigma$)	TS	Marginal detections ($3\sigma - 5\sigma$)	TS
BL Lac objects:		**BL Lac objects**:	
Mrk 421	10265.12	ZS 0214+083	14.28
Mrk 501	558.08	PKS 0422+00	9.90
1ES 1215+303	26.28	VER J0521+211	16.32
Radio Galaxies:		RX J0648.7+1516	11.78
M87	29.87	RX J1100.3+4019	13.54
		PG 1218+304	23.72
		W Comae	10.08
		Radio Galaxies:	
		3C 264	9.56

Table 1: AGNs in our sample with $TS > 9$ in the $\alpha = 2.5$ study.

follows the model by [9].

Then, we calculated the test statistic (TS) for each source, which is defined in terms of the log-likelihood ratio between the best fit point source ($\mathcal{L}_1$, source+background model) and the null hypothesis ($\mathcal{L}_0$, background-only model),

$$TS = 2\ln\left(\frac{\mathcal{L}_1}{\mathcal{L}_0}\right). \tag{2}$$

For those sources with $TS > 9$, we performed a second analysis fitting both the normalization K and the spectral index α as free parameters.

3. Results and discussion

After carrying out the initial analysis with the spectral index fixed to 2.5, we found 12 sources with $TS > 9$. From these sources, ten are classified as BL Lac objects (a subclass of blazars) and two as radio galaxies. Moreover, four presented a $TS > 25$. This represents a significant improvement in the number of detections compared to previous results, in which we found only five sources with $TS > 9$. The 12 HAWC sources are listed in Table 1 along with their TS values. In addition, Figure 1 shows the histogram of significances (defined as $s = \sqrt{TS}$) for the whole sample. In order to have a better insight, Figure 2 depicts the same histogram but excluding the two most significant sources, Mrk 421 and Mrk 501.

As we mentioned in the previous section, the 12 sources with $TS > 9$ were then fitted by allowing both the normalization and the spectral index to vary, as defined in Eq. 1. We obtained an increase in TS for every source in the sub-sample, as can be seen in Table 2. It is worth mentioning that the search on the updated data set led to the detection of a new source with $TS > 25$, the blazar PG 1218+304. However, this source is just 0.88 degrees from another source in our sample, 1ES 1215+303, which implies that we can not rule out a possible contamination between these two

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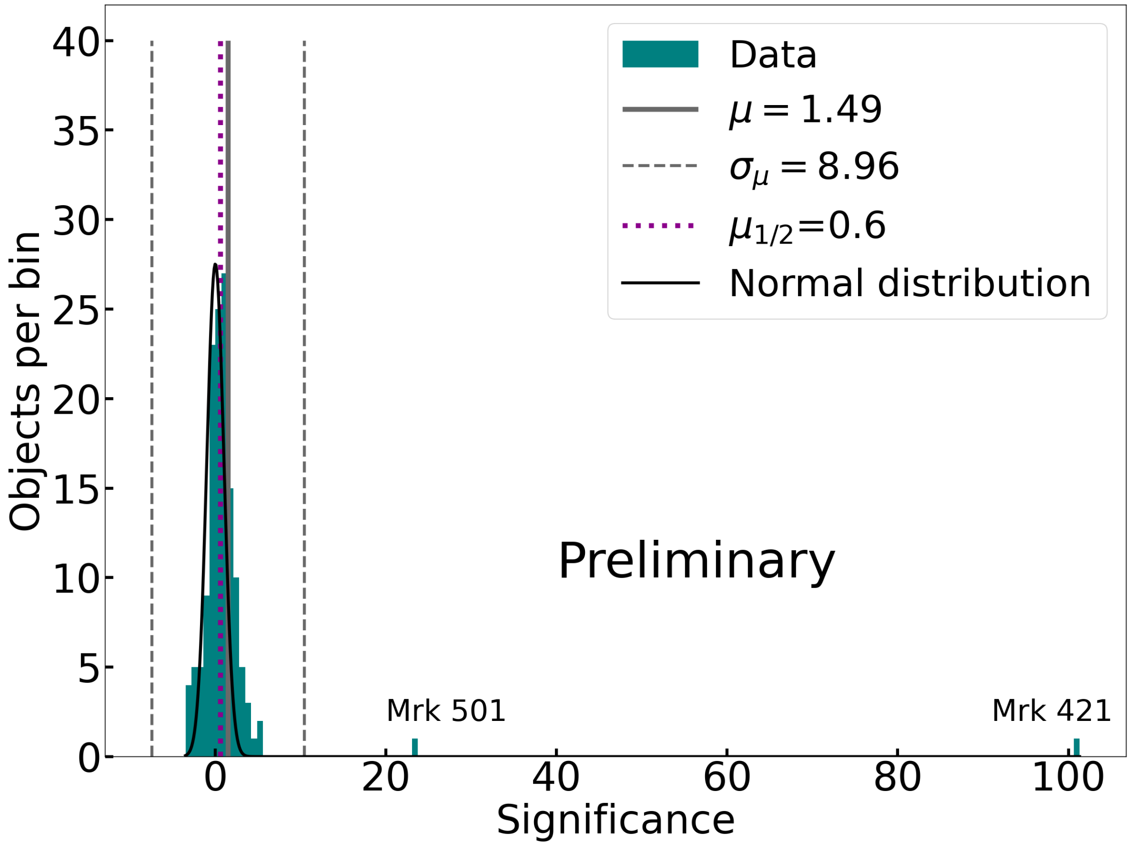

Figure 1: Histogram of significances (defined as $s = \sqrt{TS}$) for the $\alpha = 2.5$ study, including the two most significant sources (Mrk 421 and Mrk 501).

objects. Finally, Figure 3 shows the best fit values for the gamma spectral parameters in the most significant sources in our sample.

4. Concluding remarks

After analyzing 2090 of HAWC data we found 12 active galaxies, from a sample of 138 selected from the Fermi FHL catalogue, with $TS > 9$. After obtaining intrinsic gamma spectra for these 12 sources, we confirmed that three of them present a $TS > 25$, which is consistent with other HAWC analyses. In the case of other two BL Lac objects with $TS > 25$ (1ES 1215+303 and PG 1218+304), a more detailed analysis in needed to exclude a likely mutual contamination.

This work confirms the ability of HAWC to characterize the long-term VHE emission AGNs. As HAWC continues to collect gamma-ray data, we expect to improve the results on AGN long term properties in the future.

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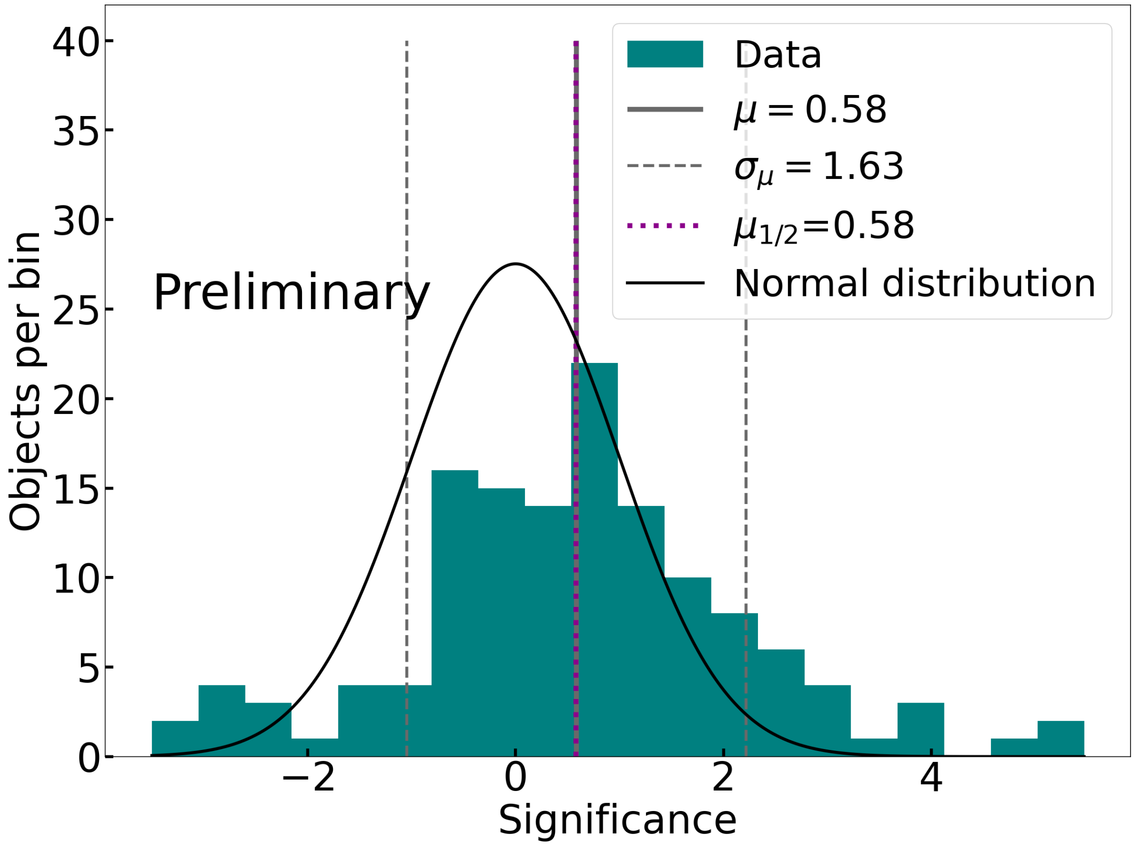

Figure 2: Histogram of significanes (defined as $s = \sqrt{TS}$) for the $\alpha = 2.5$ study, excluding the two most significant sources (Mrk 421 and Mrk 501).

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Detections ($> 5\sigma$)	TS	Marginal detections ($3\sigma - 5\sigma$)	TS
Mrk 421	10332.3	ZS 0214+083	15.474
Mrk 501	558.592	PKS 0422+00	11.541
1ES 1215+303	43.8617	TXS 0518+211	18.2545
M87	30.8741	RX J0648.7+1516	13.4317
PG 1218+304	28.4891	RX J1100.3+4019	13.5593
		W Comae	11.7698
		3C 264	9.59461

Table 2: Sources in our sample with $TS > 9$, with the TS values obtained after fitting both the normalization K and spectral index α.

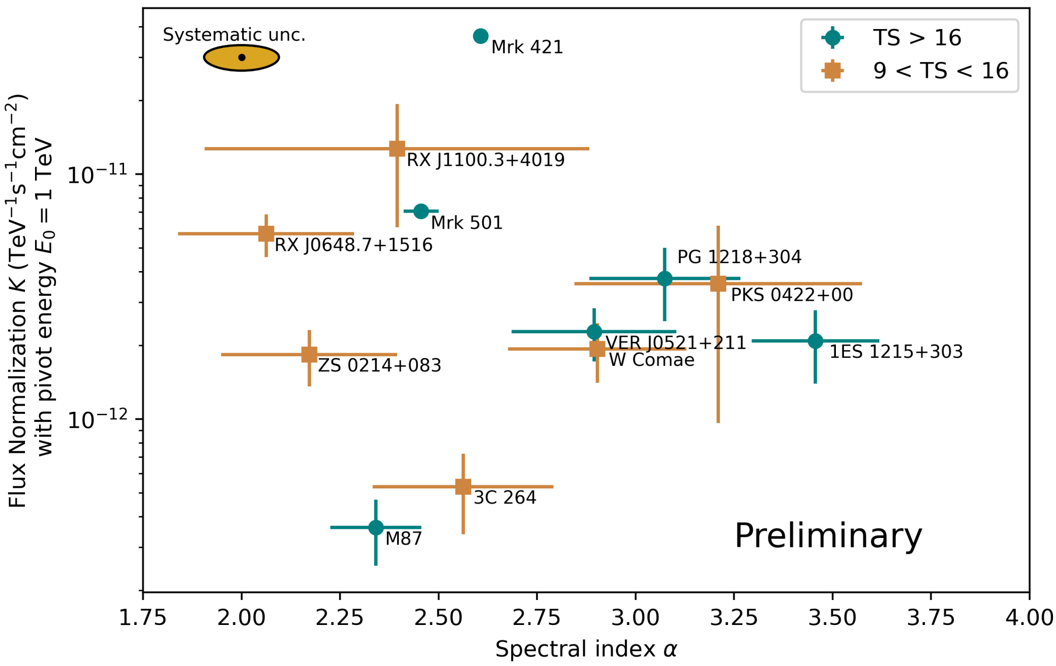

Figure 3: Best fit values of the spectral parameters (K,α) for the sources in our sample with $TS > 9$. The error bars are purely statistical, but the ellipse represents the systematic uncertainties computed for Mrk 421.

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