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Detection of HESS J2019+368: a case study of very-large-zenith angle observations with H.E.S.S.

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Observations at very large zenith angles (VLZA) can push the sensitivity of Imaging Atmospheric Cherenkov Telescopes (IACTs) towards higher energies. There are successful examples of VLZA observations presented by H.E.S.S., MAGIC and VERITAS. Besides covering a broader energy range, the operation of Cherenkov telescopes under VLZA increases the exposure for transient events observations. The updated scientific strategy of H.E.S.S. has a significant focus on the detection of transient phenomena, which makes the development of the VLZA technique of crucial importance for future observations. We present a detection of the low-altitude source HESS J2019+368 using VLZA-only operation and discuss the capabilities and limitations of the H.E.S.S. instrument for this type of observations.

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1. Introduction

Production of PeV cosmic rays in astrophysical sources has been revealed initially by Imaging Atmospheric Cherenkov Telescopes (IACT) [1, 2], however the direct detection of photons beyond 100 TeV is challenging due to limited effective area of Cherenkov telescope arrays. Commissioning of modern ground-based non-imaging gamma-ray observatories, such as HAWC and LHAASO, pushed astrophysics into PeVatron discovery epoch [3, 4].

To increase the collection area of IACTs observations at very large zenith angles (VLZA, $\theta > 60°$) are proposed [5]. The main idea is to exploit the increase of the Cherenkov light pool caused by the increased propagation lengths and projection effects (proportional to $1/\cos\theta$). With the increase of propagation length in order of magnitude from about $O(10^1)$ km to about $O(10^2)$ km the Cherenkov light pool is increased from about $O(10^{-4})$ km^2 for vertical air-showers to about $O(10^0)$ km^2 at zenith angles of about 80°. Obviously this approach has its own disadvantages including degraded angular resolution and increased energy threshold by order of magnitude, as well as additional systematic uncertainties coming from increased mass of atmosphere passed by Cherenkov light.

The capability of VLZA was demonstrated on different sources: Mkn 421 by H.E.S.S. (High Energy Stereoscopic System) [6], Crab by MAGIC [7], and Galactic Center by MAGIC [8] and VERITAS [9]. The detection of new high-energy Galactic sources by HAWC and LHAASO has triggered renewed interest in the VLZA technique.

For our study we have selected the MGRO J2019+37 [10], an extended region with unidentified origin possibly related to a pulsar wind nebula, with gamma emission detected by many observatories, including VERITAS [11] and HAWC [12], two detectors that have studied it in detail. The choice for H.E.S.S. is motivated by its visibility only under VLZA (see Fig. 1), sufficient brightness to be detected in reasonable time, and its extended dimensions. Given that H.E.S.S. cameras were recently upgraded [13, 14] these observations are the first ones to validate the VLZA performance of the array in its actual configuration.

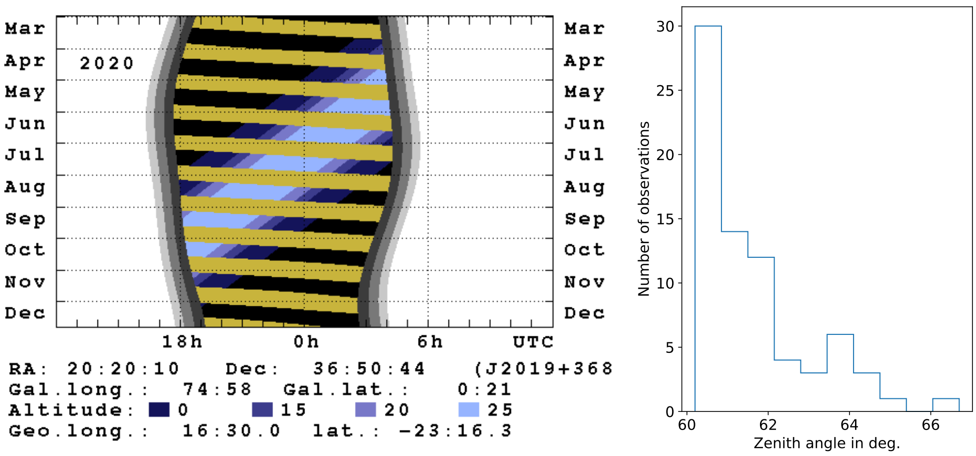

Figure 1: *Left:* visibility of MGRO J2019+37 during dark time (black bands) at H.E.S.S. geographical position in 2020. Orange bands indicate periods when Moon is above horizon. *Right:* Zenith angle distribution of H.E.S.S. observations. Average duration of each observation is about 28 minutes.

2. Observation and analysis

The H.E.S.S. is an array of four 12-m and one 28-m IACTs located in the Khomas Highland in Namibia at an altitude of 1835 m. It is capable of detecting gamma-rays from energies of a few tens of GeV to more than 100 TeV.

HESS J2019+368 was observed for about 40 h in 2020 with zeniths of $60° < \theta < 67°$ using all five H.E.S.S. telescopes both under dark and moderate moonlight conditions. Fig. 1 shows its visibility and zenith angle distribution of observations.

Since we focus on the high-energy detection, in the current work we analyzed the data from four 12-m telescopes using the *standard cuts* of the semi-analytical *Model Analysis* [15], which was cross-checked and validated with an independent event calibration and reconstruction analysis [16]. Both pipelines show the detection of the source at energies above 3 TeV with high significance exceeding 5 sigma. Significance is calculated according to Li-Ma definition [17].

Fig. 2 shows the significance map obtained by H.E.S.S. At such high zenith angles most of the detected photons have energies above 3 TeV, and the point spread function (PSF) is significantly degraded and has a 68% containment radius of about 0.14°. We fitted the source with 2D Gaussian and obtained the following results: R.A. = $(304.87 \pm 0.03)°$, dec. = $(36.80 \pm 0.01)°$, with $\sigma_x = (0.27 \pm 0.02)°$, $\sigma_y = (0.11 \pm 0.01)°$ and rotation of $18° \pm 4°$. It is worth noting, that there is still room for improvement, since H.E.S.S. analysis is not optimized for VLZA.

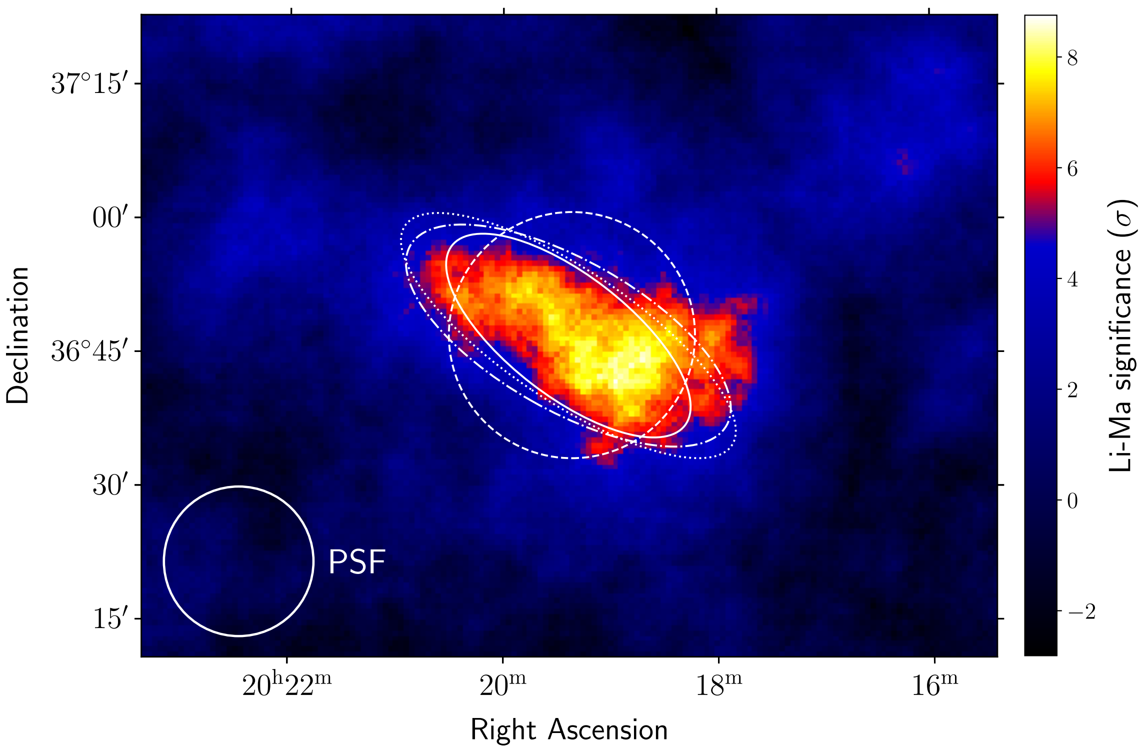

Figure 2: Significance map of HESS J2019+368 in ICRS frame obtained with oversampling of 0.14°, which corresponds to 68% containment radius of PSF at these zenith angles. The map includes 2D-Gaussian fit contours of HESS J2019+368 (solid) as well as VER J2019+368 [11] (dash-dotted) and HAWC J2019+368 [12] (dotted) contours. The dashed circle indicates spectra extraction region used in Fig. 3.

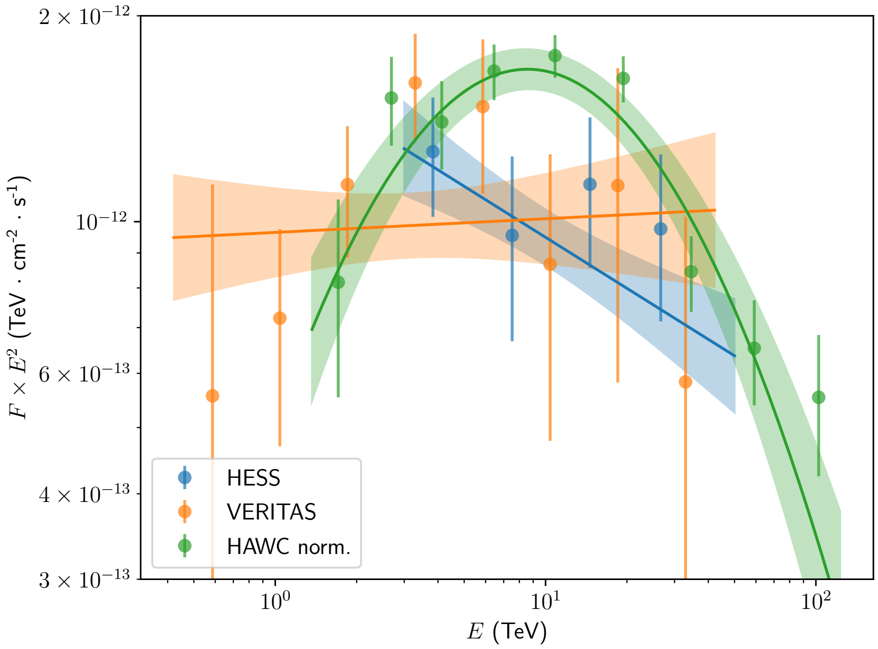

Figure 3: Comparison of HESS J2019+368 spectra. We extracted spectrum from region defined in VERITAS paper [11] to make comparison more direct (keeping in mind that our PSF is larger and non-negligible). HAWC points are normalized by the factor of 2.71 for this comparison as proposed in their original paper [12] after investigation of differences between spectra reconstruction used by HAWC and IACTs. Butterfly plots correspond to best fits as in original works. H.E.S.S. spectrum is fitted with a power-law function, and is sampled with only four points, having large uncertainties at high energies.

For the energy reconstruction we have chosen the safe threshold of 3 TeV accessible by both reconstruction pipelines and spectrum extraction region from Ref. [11]. The simple power law fit gives flux normalization $\Phi = (9.42 \pm 0.90) \times 10^{-15}$ cm^{-2} s^{-1} TeV^{-1} at $E = 10.03$ TeV with index $\Gamma = 2.25 \pm 0.10$. The comparison between VERITAS [11] and normalized HAWC [12] spectra is presented in Fig. 3. One can see that the spectral points are in satisfactory agreement between each other within statistical uncertainties. It is important to note that H.E.S.S. systematical uncertainties for this analysis are larger than for ones using data obtained with lower zenith angles due to increased mass of atmosphere traversed by Cherenkov photons. Using the aerosol data [18] for the observation period we estimated that the Cherenkov photon loss not accounted by standard analysis is of order about 10% averaging over dataset. In current analysis we do not apply these corrections, and quote the additional systematic uncertainty of this order of magnitude.

3. Conclusion and discussion

Very-large-zenith angle observations become naturally important as we attempt to detect gamma-ray emission beyond 100 TeV with IACTs. The feasibility of this technique was shown by different telescopes detecting different sources, galactic and extra-galactic, point-like and extended ones. In this work we have shown that using modern cameras and up-to-date detector response we obtained satisfactory results without additional efforts. This is a good indication, that this techniques could also extend the observation time available for transient phenomena [19].

The analysis of observations of MGRO J2019+37 region with H.E.S.S. still has room for significant improvement in different directions: improving the angular resolution using more sophisticated methods [2, 20, 21]; implementing improved atmospheric correction at VLZA; improving gamma-hadron separation using all five H.E.S.S. telescopes [22]. It is worth noting that the most of the data used actually correspond to a narrow zenith angle window of 60—62° at the edge of the used VLZA definition, so these observations might not reflect the full potential (or limitations) of VLZA data taking.

VLZA observations with the current generation of IACTs can also serve as a pathfinder not only for CTA [23], but also for next-generation telescopes aimed at the scientific goals beyond gamma-ray detection, e.g. ultra-high energy neutrino detection [24], cosmic-ray mass composition [25], and other studies accessible only by measuring highly inclined air-showers.

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