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Studies on the VHE spectrum of the radio galaxy M87 observed by HAWC

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We report the detection of TeV gamma-ray emission from M87 with the High Altitude Water Cherenkov (HAWC) observatory, marking the first time its time-integrated TeV spectrum has been measured over an extended period of approximately 6 years. The emission is consistent with a power-law spectrum with index $\alpha = 2.53 \pm 0.29$ and flux normalization $(7.09 \pm 1.24) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV, extending up to 26.5 TeV at a 1σ confidence level. This result provides the most detailed characterization of the very-high-energy (VHE) emission of M87, derived from the longest temporal coverage up to date, and offers new constraints on particle acceleration in radio galaxies.

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M87

M87 is a radio galaxy located in the Virgo cluster at a redshift of $z = 0.0044$ (16.7 ± 0.2 Mpc) [1]. It hosts a supermassive black hole (SMBH) of mass $(6.5 \pm 0.7) \times 10^9$ $M_\odot$ [2], with a prominent relativistic jet extending up to 2 kpc of longitude and oriented at angles $\geq 15°$ to our line of sight [3]. Its proximity and the orientation of its jet enable detailed multi-wavelength studies from radio to X-rays of its inner core regions [3–5]. Notably, the Event Horizon Telescope (EHT) captured the first-ever image of a SMBH in M87's core [2, 6]. In the very-high-energy (VHE) gamma-ray band, M87 serves as a key target to study emission processes and particle acceleration mechanisms, particularly for the understanding of radio galaxies' relativistic jets [7, 8].

The initial detection at GeV energies by the Imaging Atmospheric Cherenkov Telescope (IACT) HEGRA [9] was followed by multiple monitoring campaigns from the IACTs: H.E.S.S., MAGIC, and VERITAS. During periods of low-activity state, M87 was observed by all three instruments, with H.E.S.S. reporting the lowest recorded flux in 2004 [10]. Flaring episodes have also been observed in 2005 by H.E.S.S., 2008 by MAGIC, and 2010 by VERITAS [10–13]. These observations showed that both quiet-state and flare-state spectra are well described by a power-law (PL) function with no evidence of spectral cut off.

Regarding long-term monitoring, M87 was observed between 2011 and 2012 by VERITAS; where month-to-month TeV flux variability was detected, suggesting long-term spectral evolution even in quiescent state [14]. Recent monitoring by MAGIC and VERITAS from 2019 to 2022, totaling 112 and 61 hours respectively, showed no variability on daily or monthly timescales [15]. H.E.S.S. accumulated 120 hours of low-state data from 2004 to 2021, confirming that gamma-ray emission origin is consistent with the radio core across activity states [8].

Complementing VHE observations, the High Altitude Water Cherenkov (HAWC) observatory offers a distinct advantage through its continuous, wide-field monitoring capabilities. Operational since March 2015, HAWC maintains a duty cycle exceeding 95% and covers two-thirds of the sky instantaneously [16], enabling it to capture VHE gamma rays from hundreds of GeV to several hundred TeV. For technical specifications of the main array and instrumentation, refer to Abeysekara et al. [17]. Recent improvements to HAWC's reconstruction algorithms have significantly enhanced its background rejection and angular resolution, particularly from ~ 300 GeV up to hundreds of TeV energies [18]. Given that extragalactic spectra are attenuated by the Extragalactic Background Light (EBL) at TeV energies, these advancements are especially valuable for studying sources like M87. While earlier HAWC studies did not yield direct detection of M87, they contributed valuable spectral energy distribution (SED) constraints through upper limits, supporting lepto-hadronic models as responsible of its long-term emission [19].

In this proceeding, we summarized some of the results to be published in an upcoming paper regarding the study of M87 with HAWC. Using 2141 days of data, we performed a spectral analysis using HAWC's Neural Network energy estimator [18, 20].

Discussion and Conclusions

HAWC's gamma-ray spectrum of M87 is well described by a PL with a spectral index of $\alpha = 2.53 \pm 0.29$, which is softer than the indices typically reported during high-activity states and slightly higher than those observed during low-activity states previously reported by various IACTs [21, 22]. In Figure 1, the differential flux vs the spectral index is plotted for multiple observations of M87, including the results of this work. This plot indicates that the emission recorded by HAWC throughout the 2141-day observation window corresponds to a persistent low-activity state.

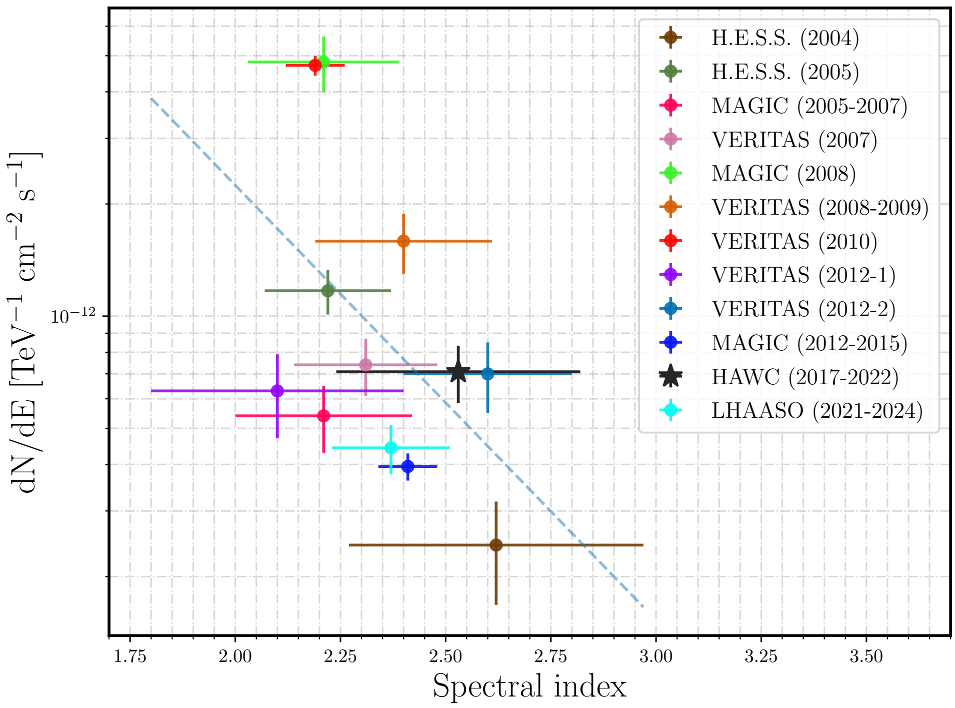

Figure 1: M87 fitted flux normalization at 1 TeV vs fitted spectral index for different observation campaigns. Dotted line represents a linear fit to the data. References.— H.E.S.S. (2004) [10], H.E.S.S. (2005) [10], MAGIC (2005-2007) [21], VERITAS (2007) [22], MAGIC (2008) [11], VERITAS (2008-2009) [12], VERITAS (2010) [13], VERITAS (2012-1) [14], VERITAS (2012-2) [14], MAGIC (2012-2015) [23], HAWC (2017-2022) (this work) and LHAASO (2021-2024) [24].

Notably, HAWC's long-term observation enable the detection of emission above 10 TeV from M87 during such a quiescent state, where comparable energies had only been observed during the 2005 flare episodes captured by H.E.S.S. [10]. The key distinction between the two observations lies in the spectral index: HAWC's measurement yields a softer spectrum compared to the harder index reported by H.E.S.S. (α = 2.22 ± 0.15). The flux measured by HAWC further supports that M87 remained in a low-activity state on average throughout the observed period, especially when contrasted with earlier IACT observations. However, HAWC's spectrum extends up to 20 TeV, an energy range previously associated only with flaring events.

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