

Searching for TeV emission from LHAASO J0341+5258 with VERITAS and HAWC

P. Bangale,^{a,*} for the VERITAS Collaboration and X. Wang^b for the HAWC Collaboration

^a*Department of Physics and Astronomy and the Bartol Research Institute,
University of Delaware, Newark, DE 19716, USA*

^b*Department of Physics,
Michigan Technological University, Houghton, MI 49931, USA*

E-mail: pbangale@udel.edu

Galactic PeVatrons are astrophysical sources accelerating particles up to a few PeV ($\sim 10^{15}$ eV) energies. The primary signature of 100 TeV γ rays may come from PeV protons or multi-hundred TeV (not PeV) electrons. The search for PeVatrons has been one of the key science topics for VERITAS and HAWC. In 2021, LHAASO detected 14 steady γ -ray sources with photon energies above 100 TeV, up to 1.4 PeV. This provides a clear list of PeVatron candidates for further study with VERITAS and HAWC. Most of these sources contain possible source associations, such as supernova remnants, pulsar wind nebulae, and stellar clusters. However, two sources: LHAASO J2108+5157 and LHAASO J0341+5258, do not have any such counterparts. Therefore, multiwavelength observations are required to identify the objects responsible for the UHE γ rays, to understand the source morphology and association, and to shed light on the emission processes. Here, we will present the status of VERITAS/HAWC observations and results for the LHAASO PeVatron candidate J0341+5258, and also discuss the VERITAS PeVatron search in general.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan



*Speaker

1. Introduction

The study of PeVatrons, particularly identifying hadronic PeVatrons, is a crucial step towards understanding the longstanding problem of cosmic ray origin. γ -ray observations in the ultra-high energy (UHE, $E > 100$ TeV) band are essential for PeVatron searches. The current generation of imaging atmospheric Cherenkov telescopes (IACTs) are most sensitive to γ -ray photons around TeV energies. To study γ rays above ~ 10 TeV requires a large effective area, and a long exposure, which is limited by the moderate field of view (FoV) and the duty cycle of current IACTs. Extensive air shower arrays, such as Tibet-As γ , HAWC and LHAASO, have a wide FoV and high-duty cycle, which is useful in detecting γ -ray sources beyond energies of tens of TeV, and up into the UHE band [1, 2]. Probing the TeV–PeV energy band is crucial for the source identification to explain the cosmic rays up to the knee and beyond.

The search for PeVatrons has been one of the key science topics for VERITAS and HAWC. VERITAS search has involved observations of young supernova remnants (SNR) such as Cas A [3] and Tycho’s SNR [4], in which spectral cut-offs were observed around ~ 2 TeV. In addition, observations of unidentified, hard-spectrum sources such as MGRO J1908+06, MGRO J2019+37, and VER J2227+608 (SNR G106.4+2.7 region) [5–7], and HAWC sources from the second catalog [20] were also performed. In 2021, LHAASO detected 14 steady γ -ray sources with photon energies above 100 TeV, up to 1.4 PeV [9–11], probing the long-standing question whether hadronic PeVatrons exist. The LHAASO results provided a clear list of PeVatron candidates for further study with VERITAS and HAWC. Most of these sources contain possible source associations, such as SNRs, pulsar wind nebulae (PWN), or stellar clusters, except LHAASO J0341+5258 [10] and LHAASO J2108+5157 [12]; which are without any such counterparts. Here we present a multi-wavelength study of LHAASO J0341+5258 to provide insight into the source nature and properties.

2. Observations and Results

In 2021, LHAASO reported the discovery of a new unidentified extended γ -ray source LHAASO J0341+5258 [R.A. = $(55.34 \pm 0.11)^\circ$ and DEC. = $(52.97 \pm 0.07)^\circ$] in the Galactic plane [10] using 308.33 days of Kilometer Squared Array (KM2A) data. The source was detected with a significance of 6σ , an angular size of $(0.29 \pm 0.06_{stat} \pm 0.02_{sys})^\circ$, and approximately 20% of the Crab flux above 25 TeV. CO observations with the Milky Way Imaging Scroll Painting (MWISP) project [13] of the LHAASO J0341+5257 region show partially overlapping molecular gas in the form of a half-shell structure [10]. The total mass of gas estimated using these data within 1° of the LHAASO source is about $10^3 M_\odot$ assuming a distance of 1 kpc, and there is no clear CO emission observed at larger distances. The detection of a ^{13}CO line in the enhanced ^{12}CO emission region from the half-shell structure, even if the total CO emission is not bright in this region, indicates the existence of dense clumps.

Recently, LHAASO published its first full catalog [14] of 90 sources including 43 UHE sources above 100 TeV using 508 days of data collected by the Water Cherenkov Detector Array (WCDA) and 933 days of data recorded by the KM2A. In this catalogue, they resolved LHAASO J0341+5258 into two sources using KM2A (1LHAASO J0339+5307 and 1LHAASO J0343+5254u*). More-

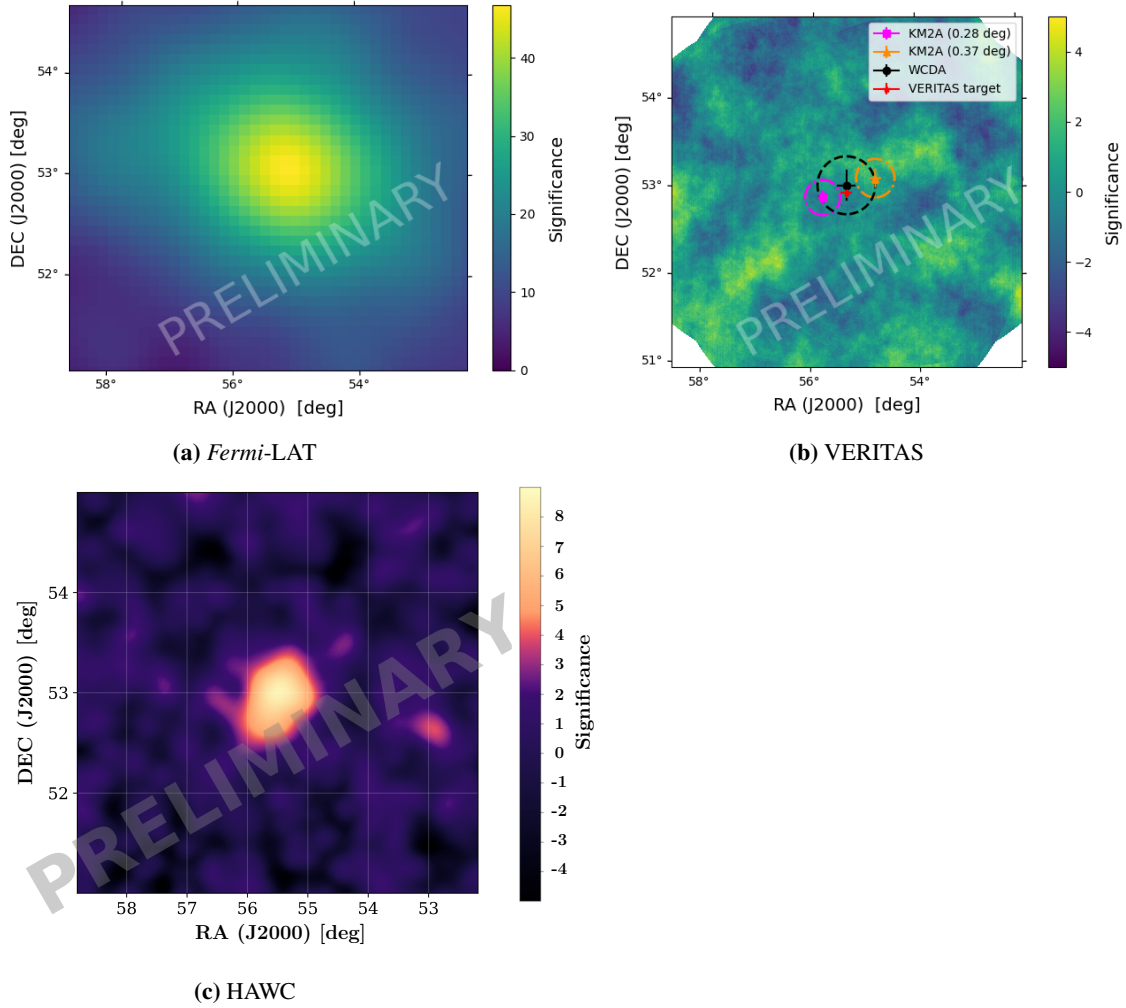


Figure 1: Significance maps for *Fermi*-LAT, VERITAS, and HAWC data in the region centered on LHAASO J0341+5258 position. The source is detected clearly in *Fermi*-LAT and HAWC data, but there is no significant detection in VERITAS data. The WCDA extension region is shown in a dashed black circle, and two extension regions corresponding to KM2A with the 0.28° and 0.37° offset are shown in dot-dashed magenta and orange circles, respectively, in the VERITAS significance map. Note that these extension regions are the 39% containment radius of the 2D-Gaussian model (r_{39} region) reported in the LHAASO catalog [14].

over, 1LHAASO J0343+5254u* was also detected in the 1-25 TeV energy range using WCDA detector. Since it covers the same energy range as WCDA, VERITAS can, in principle, provide a complementary view of this source but with the added advantage of better angular and energy resolution. 1LHAASO J0343+5254u* was detected with a test statistic (TS) of 94.1 and had a similar extension to LHAASO J0341+5258 (0.33 ± 0.05)°. With KM2A, 1LHAASO J0339+5307 was detected at an offset from the position of LHAASO J0341+5258 of 0.37°, with a TS=144, and extension < 0.22 °, whereas 1LHAASO J0343+5254u* was detected at an offset of 0.28°, TS=388.1 and extension of (0.20 ± 0.02)°.

The closest unidentified GeV source, 4FGL J0340.4+5302 [15], is located at an angular distance

of 0.16° from the position of LHAASO J0341+5258 and is contained within the reported angular extension of LHAASO J0341+5258. Therefore, to investigate further, we have performed a dedicated binned likelihood analysis using `fermipy v1.2` [16] for *Fermi*-LAT pass8 data from Aug. 2008 to Apr. 2023. The region of interest was centered on the position of LHAASO J0341+5258 for γ rays in the energy range of 100 MeV to 1 TeV. The events were binned into 0.1° spatial bins and two logarithmic energy bins per decade. The source is detected with a significance of $\sim 62\sigma$ (TS=3888.3) (figure 1a). The best-fit central position is found to be 0.15° away from LHAASO J0341+5258, which is consistent with the position determined by LHAASO. The source is specified as point-like as the TS value of the extension hypothesis is ~ 3.52 , resulting in the 95% upper limit of $\leq 0.20^\circ$ on the extension. The spectrum of 4FGL J0340.4+5302 is significantly curved; therefore, we modeled it using a log-parabola function. The best-fit spectral parameters of the log-parabola model are an energy flux of $(5.1 \pm 0.1) \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$, spectral index $\alpha = 3.86 \pm 0.06$, and $\beta = 0.53 \pm 0.02$ (figure 2). The overall spectrum is very soft, and no significant emission above 2 GeV is detected. 95% C.L. upper limits are derived for the flux above 2 GeV.

To investigate the TeV counterparts, we have searched VERITAS [17] and HAWC [20] data. VERITAS observations totalling 50 hrs were taken from Oct. 2021 - Jan. 2022 and Sept. 2022 - Jan. 2023, where observations were stopped in the gaps due to the source visibility and for the annual Arizona monsoon season. The analysis was performed using the `EventDisplay` analysis package [18] and then cross-checked with the `VEGAS` analysis package [19]. Considering the 0.33° source extension of LHAASO J0341+5258 from WCDA, we have searched VERITAS data with an extended source analysis using an integration region θ of 0.25° centered around the LHAASO J0341+5258 position. No significant emission was detected in these data (figure 1b). 99% C.L. upper limits were derived for three logarithmic energy bins per decade in the 0.5 to 31.6 TeV energy range (figure 2 and table 1).

Energy [TeV]	VERITAS Upper limits [TeV cm $^{-2}$ s $^{-1}$]
$1^{+2.0}_{-0.5}$	2.79×10^{-13}
$3.981^{+7.9}_{-2.0}$	3.16×10^{-13}
$15.849^{+31.6}_{-7.9}$	1.03×10^{-12}

Table 1: The 99% C.L. upper limits are derived from the 50 hrs of VERITAS data using an integration region of 0.25° centered around the LHAASO J0341+5258 position.

For the HAWC analysis, we used 2582 days of fHit dataset from Nov. 2014 to June 2022. We binned the data using the fraction of available PMT channels¹, as described in the HAWC Crab analysis from 2017 [20]. We choose a circular region of interest with a radius of 3° around the LHAASO J0341+5258 position. The source was detected with a significance of $\sim 8.4\sigma$ (figure 1c). Both the point source model and extended source model with a simple power law are tested, but the extended source template is not preferred over point-source template. The 95% C.L. upper limit on extension is 0.20° . Hence further analysis was performed using a point source assumption.

¹We calculate fraction of PMT as `PMT_triggered/PMT_available` for each event

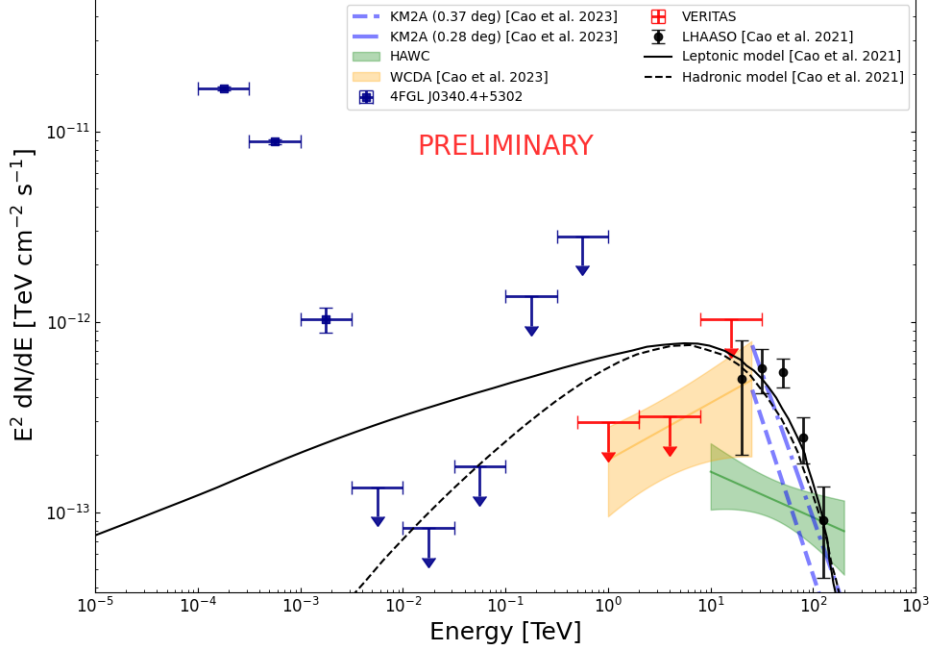


Figure 2: Multiwavelength spectral energy distribution using the *Fermi*-LAT, VERITAS, HAWC, and LHAASO data. VERITAS upper limits of 99% C.L. (red) are derived using an integration region of 0.25° centered around the LHAASO J0341+5258 position. Note that these limits are not directly comparable with the LHAASO flux points due to the differences in the source integration region (see text for more details).

The resulting spectrum was fitted with a simple power-law using a spectral index of -2.24 ± 0.22 , normalization of $1.16^{+0.32}_{-0.24} \times 10^{-13} \text{ TeV cm}^{-2} \text{ s}^{-1}$ for pivot energy of 40 TeV. Further study of the source morphology and the shape of the energy spectrum is ongoing.

3. Discussion

The multi-wavelength spectral energy distribution (SED) is built using *Fermi*-LAT, VERITAS, HAWC, and LHAASO data as shown in figure 2. We have also added WCDA and KM2A spectra provided by the first LHAASO catalog for comparison. Clearly, VERITAS upper limits already prove important, as they exclude the existing leptonic and hadronic emission models provided by LHAASO [10]. In addition, these limits are compatible with the recently-reported WCDA spectral band, confirming the hard spectrum of LHAASO J0341+5258 when extrapolating toward low energies. One important subtlety to note is that the VERITAS upper limits are not directly comparable to LHAASO, as the VERITAS integration region is significantly smaller than the 39% containment radius of the 2D-Gaussian model (r_{39}) region reported by WCDA. Using a smooth, symmetrical 2D-Gaussian form for the emission, as assumed by WCDA, approximately ~25% of the total γ -ray flux is contained within the VERITAS integration region. However, in reality the situation is likely more complex, as the source region may include emission components with significant asymmetries, non-uniformities, and multiple source components. The selection of integration region for VERITAS was based on the original LHAASO J0341+5258 results from

[10] and on considerations of signal-to-background ratio. For the current HAWC spectral analysis, using a simple power-law, the HAWC spectral band lies between the energy ranges of WCDA and KM2A. The LHAASO catalog paper indicates a possible transition of spectral indices in this region, around tens of TeV. HAWC observations and spectral fitting should allow to study and refine the measurement of this transition. In the future, we plan to use a log-parabola as a fitting function to test for possible spectral curvature, which might provide more consistency with LHAASO data.

Given the spatial coincidence between 4FGL J0340.4+5302 and LHAASO J0341+5258, one possible scenario is that both the 4FGL and LHAASO sources have a common origin. Moreover, the 4FGL J0340.4+5302 spectrum shows a sharp cutoff around 2 GeV, a typical signature of the GeV γ -ray emission of pulsars. This implies that the TeV emission is more likely of leptonic origin, resulting from the inverse Compton scattering of relativistic electrons in the surrounding PWN or a pulsar halo [21, 22]. The caveat for this scenario is the lack of detection of a powerful pulsar, which could be due to the absence of a pulsar, misalignment of the pulsar beam to the line of sight of the observer, or the spin-down luminosity limit of pulsar being below the level required to produce detectable emission [23]. As a molecular cloud partially overlaps LHAASO J0341+5257 region, an alternative possibility is a hadronic emission scenario, which could be explained by an old SNR, where cosmic rays have already escaped the SNR, encountering a nearby molecular cloud and being accumulated in a nearby but presently invisible SNR [24]. Our next step is to perform detailed multiwavelength spectral modeling to investigate the various possible emission scenarios, where the upper limits from VERITAS and *Fermi*-LAT will play a key role.

Acknowledgments

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Helmholtz Association in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

We acknowledge the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México, grants 271051, 232656, 260378, 179588, 254964, 258865, 243290, 132197, A1-S-46288, A1-S-22784, CF-2023-I-645, cátedras 873, 1563, 341, 323, Red HAWC, México; DGAPA-UNAM grants IG101323, IN111716-3, IN111419, IA102019, IN106521, IN110621, IN110521, IN102223; VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant, DEC-2017/27/B/ST9/02272; Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - Newton Advanced Fellowship 180385; Generalitat Valenciana, grant CIDEAGENT/2018/034; The Program

Management Unit for Human Resources & Institutional Development, Research and Innovation, NXPO (grant number B16F630069); Coordinación General Académica e Innovación (CGAI-UdeG), PRODEP-SEP UDG-CA-499; Institute of Cosmic Ray Research (ICRR), University of Tokyo. H.F. acknowledges support by NASA under award number 80GSFC21M0002. We also acknowledge the significant contributions over many years of Stefan Westerhoff, Gaurang Yodh and Arnulfo Zepeda Dominguez, all deceased members of the HAWC collaboration. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for technical support.

References

- [1] F. Aharonian et al. (Tibet AS γ Collaboration), *First Detection of Photons with Energy beyond 100 TeV from an Astrophysical Source*, 2019, Phys. Rev. Lett., **123**, 051101, <https://doi.org/10.1103/PhysRevLett.123.051101>
- [2] Abeysekara A. U. et al. (HAWC Collaboration), *Multiple Galactic Sources with Emission Above 56 TeV Detected by HAWC*, 2019, Phys. Rev. Lett., **124**, 021102, <https://doi.org/10.1103/PhysRevLett.124.021102>
- [3] Abeysekara A. U. et al., *Evidence for Proton Acceleration up to TeV Energies Based on VERITAS and Fermi-LAT Observations of the Cas A SNR*, 2020, ApJ, **894**, 51, <https://doi.org/10.3847/1538-4357/ab8310>
- [4] Archambault S. et al., *Gamma-Ray Observations of Tycho's Supernova Remnant with VERITAS and Fermi*, 2017, ApJ, **836**, 23, <https://doi.org/10.3847/1538-4357/836/1/23>
- [5] Aliu E. et al., *INVESTIGATING THE TeV MORPHOLOGY OF MGRO J1908+06 WITH VERITAS*, 2020, ApJ, **787**, 166, <https://doi.org/10.1088/0004-637X/788/1/78>
- [6] Aliu E. et al., *SPATIALLY RESOLVING THE VERY HIGH ENERGY EMISSION FROM MGRO J2019+37 WITH VERITAS*, 2020, ApJ, **788**, 78, <https://doi.org/10.1088/0004-637X/788/1/78>
- [7] Acciari, V. A. et al., *Detection of Extended VHE Gamma Ray Emission from G106.3+2.7 with Veritas*, 2009, ApJL, **703**, L6, <https://doi.org/10.1088/0004-637X/703/1/L6>
- [20] Abeysekara, A. U. et al., *The 2HWC HAWC Observatory Gamma-Ray Catalog*, 2017, ApJ, **843**, 40, <https://doi.org/10.3847/1538-4357/aa7556>
- [9] Cao Z. et al., *Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources*, 2021, Nature, **594**, 33, <https://doi.org/10.1038/s41586-021-03498-z>
- [10] Cao Z. et al., *Discovery of a New Gamma-Ray Source, LHAASO J0341+5258, with Emission up to 200 TeV*, 2021, ApJL, **917**, L4, <https://doi.org/10.3847/2041-8213/ac0fd5>
- [11] Aharonian F. et al. (LHAASO Collaboration), *Extended Very-High-Energy Gamma-Ray Emission Surrounding PSR J0622+3749 Observed by LHAASO-KM2A*, 2021, Phys. Rev. Lett., **126**, 241103, <https://doi.org/10.1103/PhysRevLett.126.241103>

- [12] Cao Z. et al., *Discovery of the Ultrahigh-energy Gamma-Ray Source LHAASO J2108+5157*, 2021, ApJL, **919**, L22, <https://doi.org/10.3847/2041-8213/ac2579>
- [13] Su, Y. et al., *The Milky Way Imaging Scroll Painting (MWISP): Project Details and Initial Results from the Galactic Longitudes of 25.°8-49.°7*, 2019, ApJS, **240**, 9, <https://doi.org/10.3847/1538-4365/aaf1c8>
- [14] Cao, Z. et al., *The First LHAASO Catalog of Gamma-Ray Sources*, 2023, arXiv:2305.17030, <https://doi.org/10.48550/arXiv.2305.17030>
- [15] Abdollahi S. et al., *Fermi Large Area Telescope Fourth Source Catalog*, 2020, ApJS, **247**, 33, <https://doi.org/10.3847/1538-4365/ab6bcb>
- [16] Wood M. et al., *Fermipy: An open-source Python package for analysis of Fermi-LAT Data*, International Cosmic Ray Conference Proceeding, **301**, 824, <https://doi.org/10.22323/1.301.0824>
- [17] Park, N. & VERITAS Collaboration, *Performance of the VERITAS experiment*, 2015, International Cosmic Ray Conference Proceeding, **34**, 771, <https://doi.org/10.22323/1.236.0771>
- [18] Maier G. & Holder, J., *Eventdisplay: An Analysis and Reconstruction Package for Ground-based Gamma-ray Astronomy*, Proceedings of Science, 2017, **301.**, 747, <https://doi.org/10.48550/arXiv.1708.04048>
- [19] Cogan, P., *VEGAS, the VERITAS Gamma-ray Analysis Suite*, 2008, International Cosmic Ray Conference Proceeding, **3**, 1385 <https://doi.org/10.48550/arXiv.0709.4233>
- [20] Abeysekara, A. U. et al., *Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory* 2017, ApJ, **843**, 39, <https://doi.org/10.3847/1538-4357/aa7555>
- [21] Aharonian, F. et al., *The Crab Nebula and Pulsar between 500 GeV and 80 TeV: Observations with the HEGRA Stereoscopic Air Cerenkov Telescopes*, 2004, ApJ, **614**, 897, <https://doi.org/10.1086/423931>
- [22] Sudoh, T., Linden, T., & Beacom, J. F., *TeV halos are everywhere: Prospects for new discoveries*, 2019, Phys. Rev. D, **100**, 043016, <https://doi.org/10.1103/PhysRevD.100.043016>
- [23] Guillemot L. et al., *The gamma-ray millisecond pulsar deathline, revisited*, 2015, **587**, A109, <https://doi.org/10.1051/0004-6361/201527847>
- [24] Gabici, S., Aharonian, F. A., & Blasi, P., *Gamma rays from molecular clouds*, 2007, ApSS, **309**, 365, <https://doi.org/10.1007/s10509-007-9427-6>

All Authors and Affiliations

VERITAS COLLABORATION

A. Acharyya¹, C. B. Adams², A. Archer³, P. Bangale⁴, J. T. Bartkoske⁵, P. Batista⁶, W. Benbow⁷, J. L. Christiansen⁸, A. J. Chromey⁷, A. Duerr⁵, M. Errando⁹, Q. Feng⁷, G. M. Foote⁴, L. Fortson¹⁰, A. Furniss^{11,12}, W. Hanlon⁷, O. Hervet¹², C. E. Hinrichs^{7,13}, J. Hoang¹², J. Holder⁴, Z. Hughes⁹, T. B. Humensky^{14,15}, W. Jin¹, M. N. Johnson¹², M. Kertzman³, M. Kherlakian⁶, D. Kieda⁵, T. K. Kleiner⁶, N. Korzoun⁴, S. Kumar¹⁴, M. J. Lang¹⁶, M. Lundy¹⁷, G. Maier⁶, C. E. McGrath¹⁸, M. J. Millard¹⁹, C. L. Mooney⁴, P. Moriarty¹⁶, R. Mukherjee²⁰, S. O'Brien^{17,21}, R. A. Ong²², N. Park²³, C. Poggemann⁸, M. Pohl^{24,6}, E. Pueschel⁶, J. Quinn¹⁸, P. L. Rabinowitz⁹, K. Ragan¹⁷, P. T. Reynolds²⁵, D. Ribeiro¹⁰, E. Roache⁷, J. L. Ryan²², I. Sadeh⁶, L. Saha⁷, M. Santander¹, G. H. Sembroski²⁶, R. Shang²⁰, M. Spletstoesser¹², A. K. Talluri¹⁰, J. V. Tucci²⁷, V. V. Vassiliev²², A. Weinstein²⁸, D. A. Williams¹², S. L. Wong¹⁷, and J. Woo²⁹

HAWC COLLABORATION

A. Albert³⁰, R. Alfaro³¹, C. Alvarez³², A. Andrés³³, J.C. Arteaga-Velázquez³⁴, D. Avila Rojas³¹, H.A. Ayala Solares³⁵, R. Babu³⁶, E. Belmont-Moreno³¹, K.S. Caballero-Mora³², T. Capistrán³³, S. Yun-Cárcamo³⁷, A. Carramiñana³⁸, F. Carreón³³, U. Cott³⁴, J. Cotzomi⁵⁵, S. Coutiño de León³⁹, E. De la Fuente⁴⁰, D. Depaoli⁴¹, C. de León³⁴, R. Diaz Hernandez³⁸, J.C. Díaz-Vélez⁴⁰, B.L. Dingus³⁰, M. Durocher³⁰, M.A. DuVernois³⁹, K. Engel³⁷, C. Espinoza³¹, K.L. Fan³⁷, K. Fang³⁹, N.I. Fraija³³, J.A. García-González⁴², F. Garfias³³, H. Goksu⁴¹, M.M. González³³, J.A. Goodman³⁷, S. Groetsch³⁶, J.P. Harding³⁰, S. Hernandez³¹, I. Herzog⁴³, J. Hinton⁴¹, D. Huang³⁶, F. Hueyotl-Zahuantitla³², P. Hüntemeyer³⁶, A. Iriarte³³, V. Joshi⁵⁷, S. Kaufmann⁴⁴, D. Kieda⁴⁵, A. Lara⁴⁶, J. Lee⁴⁷, W.H. Lee³³, H. León Vargas³¹, J. Linnemann⁴³, A.L. Longinotti³³, G. Luis-Raya⁴⁴, K. Malone⁴⁸, J. Martínez-Castro⁴⁹, J.A.J. Matthews³⁰, P. Miranda-Romagnoli⁵¹, J. Montes³³, J.A. Morales-Soto³⁴, M. Mostafá³⁵, L. Nellen⁵², M.U. Nisa⁴³, R. Noriega-Papaqui⁵¹, L. Olivera-Nieto⁴¹, N. Omodei⁵³, Y. Pérez Araujo³³, E.G. Pérez-Pérez⁴⁴, A. Pratts³¹, C.D. Rho⁵⁴, D. Rosa-Gonzalez³⁸, E. Ruiz-Velasco⁴¹, H. Salazar⁵⁵, D. Salazar-Gallegos⁴³, A. Sandoval³¹, M. Schneider³⁷, G. Schwefel⁴¹, J. Serna-Franco³¹, A.J. Smith³⁷, Y. Son⁴⁷, R.W. Springer⁴⁵, O. Tibolla⁴⁴, K. Tollefson⁴³, I. Torres³⁸, R. Torres-Escobedo⁵⁶, R. Turner³⁶, F. Ureña-Mena³⁸, E. Varela⁵⁵, L. Villaseñor⁵⁵, X. Wang³⁶, I.J. Watson⁴⁷, F. Werner⁴¹, K. Whitaker³⁵, E. Wilcox³⁷, H. Wu³⁹, and H. Zhou⁵⁶

¹Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA

²Physics Department, Columbia University, New York, NY 10027, USA

³Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA

⁴Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

⁵Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

⁶DESY, Platanenallee 6, 15738 Zeuthen, Germany

⁷Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA

⁸Physics Department, California Polytechnic State University, San Luis Obispo, CA 94307, USA

⁹Department of Physics, Washington University, St. Louis, MO 63130, USA

¹⁰School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

¹¹Department of Physics, California State University - East Bay, Hayward, CA 94542, USA

¹²Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA

¹³Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755 USA

¹⁴Department of Physics, University of Maryland, College Park, MD, USA

¹⁵NASA GSFC, Greenbelt, MD 20771, USA

¹⁶School of Natural Sciences, University of Galway, University Road, Galway, H91 TK33, Ireland

¹⁷Physics Department, McGill University, Montreal, QC H3A 2T8, Canada

¹⁸School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

¹⁹Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA

²⁰Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA

²¹ Arthur B. McDonald Canadian Astroparticle Physics Research Institute, 64 Bader Lane, Queen's University, Kingston, ON Canada, K7L 3N6

²²Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

²³Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada

²⁴Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany

²⁵Department of Physical Sciences, Munster Technological University, Bishopstown, Cork, T12 P928, Ireland

²⁶Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA

²⁷Department of Physics, Indiana University-Purdue University Indianapolis, Indianapolis, IN 46202, USA

²⁸Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

²⁹Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

- ³⁰Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA,
³¹Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, México,
³²Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México,
³³Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México,
³⁴Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México,
³⁵Department of Physics, Pennsylvania State University, University Park, PA, USA,
³⁶Department of Physics, Michigan Technological University, Houghton, MI, USA,
³⁷Department of Physics, University of Maryland, College Park, MD, USA,
³⁸Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México,
³⁹Department of Physics, University of Wisconsin-Madison, Madison, WI, USA,
⁴⁰CUCEI, CUCEA, Universidad de Guadalajara, Guadalajara, Jalisco, México,
⁴¹Max-Planck Institute for Nuclear Physics, Heidelberg, Germany,
⁴²Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, México,
⁴³Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA,
⁴⁴Universidad Politécnica de Pachuca, Pachuca, Hgo, México,
⁴⁵Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA,
⁴⁶Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México,
⁴⁷University of Seoul, Seoul, Rep. of Korea,
⁴⁸Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, NM USA
⁴⁹Centro de Investigación en Computación, Instituto Politécnico Nacional, Ciudad de México, México,
⁵⁰Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA,
⁵¹Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., México,
⁵²Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, México,
⁵³Stanford University, Stanford, CA, USA,
⁵⁴Department of Physics, Sungkyunkwan University, Suwon, South Korea,
⁵⁵Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, México,
⁵⁶Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China,
⁵⁷Erlangen Centre for Astroparticle Physics, Friedrich Alexander Universität, Erlangen, BY, Germany