PROCEEDINGS OF SCIENCE

Low energy performance boost through a hardware stereoscopic trigger between CTA LST-1 and MAGIC

J. Baxter,[a,*] **J. A. Barrio,**[b] **M. Bitossi,**[c] **A. Donini,**[d] **D. Mazin,**[a,e] **R. Paoletti,**[c,f] **A. Pérez Aguilera**[b] **and L. Á. Tejedor Álvarez**[b] **on Behalf of the CTA-LST Project and MAGIC collaboration**

[a] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[b] *IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, Spain*
[c] *Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Pisa, 56127 Pisa, Italy*
[d] *Istituto Nazionale di Astrofisica (INAF), Osservatorio Astronomico di Roma, Italy*
[e] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*
[f] *Università degli Studi di Siena, via Roma 56, 53100 Siena*

E-mail: `joshua28@icrr.u-tokyo.ac.jp`, `joshuaicrr@gmail.com`

The next generation facility for gamma-ray ground-based observations is the Cherenkov Telescope Array (CTA) observatory, which comprises three types of imaging atmospheric Cherenkov telescopes (IACTs). The Large-Sized Telescopes (LSTs) of CTA are the largest telescope type with a mirror dish of 23 m diameter. They cover the low energy end of the accessible gamma-ray energies for IACTs, starting from about 20 GeV up to a few TeV. The first LST prototype, known as LST-1, was officially inaugurated at the Observatorio del Roque de Los Muchachos in La Palma (Canary Islands, Spain) in 2018 and has since performed calibration observations of various known gamma-ray sources. Additionally, the site houses the MAGIC telescopes, two 17 m IACTs situated approximately 100 m away from LST-1, which have been performing stereo observations since 2009. Currently, joint observations between LST-1 and MAGIC are being carried on, and the data taken independently by the two IACT systems is analyzed by combining events via software. However, this method increases the energy threshold, as it discards all but the relatively high-energy events triggered by all three telescopes. To address this issue, we have developed a novel hardware stereo trigger system between LST-1 and MAGIC, which is capable of handling events triggered by any-two out of the three telescopes. In this contribution, we will report on the performance estimation of joint LST-1 and MAGIC observations using the hardware trigger.

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

---

[*] Speaker

https://pos.sissa.it/

PoS(ICRC2023)700

1. Introduction

The Cherenkov Telescope Array (CTA) is the forthcoming generation of terrestrial gamma-ray observatories, sensitive to an extensive energy bandwidth from 20 GeV to 300 TeV [1]. Designed to observe the entire sky, the observatory will be constructed in both the Northern and Southern Hemispheres. The Northern Hemisphere site, situated at the Observatorio Roque de los Muchachos in La Palma, Spain, at an altitude of 2200 m.a.s.l, comprises 4 Large-Sized Telescopes (LSTs) and 15 Medium Size Telescopes (MSTs). Of these, the inaugural Large-Sized Telescope, LST-1, was completed in 2018 and has embarked on scientific observations since 2019. Boasting its substantial 23-meter diameter reflector, LST-1 possesses the highest sensitivity within the lowest energy domain of the CTA [2, 3].

The MAGIC telescopes, a pair of current generation IACT with a 17 m aperture mirror situated approximately 100 m from LST-1 (Figure 1), has been observing in stereoscopic mode since 2009. For sources with a spectral index of -2.6 at low zenith angles (zd < 35 deg), MAGIC is estimated to have an energy threshold (characterized by the peak resulting from a Gaussian fit to the differential true energy distribution of triggered events) of about 50 GeV for the standard trigger [4]. MAGIC is generally operated to record only stereo events that trigger both telescopes, and operates independently of LST-1.

LST-1 and MAGIC can trigger identical Cherenkov shower events due to their proximity, and joint observations have been performed by searching for independently triggered events offline [8]. Joint observations with this approach can only handle events triggered by all three telescopes, as there is no physical trigger exchange between LST-1 and MAGIC. To overcome this, we have implemented a Hardware Stereo Trigger (**HaST**) between LST-1 and MAGIC, constructing a system capable of recording relatively faint low-energy shower events triggered by any-two telescopes amongst LST-1 and MAGIC, thereby enhancing the performance of joint observations.

Figure 1: Photograph of LST-1 and MAGIC in La Palma (credit: Akira Okumura). From left to right: LST-1, MAGIC-II, MAGIC-I. The longest distance between LST-1 and MAGIC-I is 156 m apart.

2. Implementation of the hardware stereo trigger system

Both the LST-1 and MAGIC telescopes have a multilevel trigger architecture to acknowledge the occurrence of a potentially interesting event. Once there is a positive result from the trigger system for a given event, the digitizing and the data acquisition systems are triggered. This multilevel trigger architecture is structured hierarchically as: the pixel level trigger (L0), the telescope camera level trigger (L1) and the array, or the stereo [5], level trigger (the temporal coincidence of several camera level triggers from different telescopes). In the case of LST-1, all the trigger system components are integrated inside the telescope camera, while the trigger system of MAGIC is centralized in a building called the Counting House (CH).

The implementation schematic of the HaST system is illustrated in Figure 2. To facilitate the transmission of trigger signals, we implemented a new optical fiber cable between LST-1 and the MAGIC CH. After the trigger signal enters the MAGIC CH via this optical fiber, the LST-1 L1 signal is converted into a digital signal by a newly fabricated Electro-Optical Transceiver (EOT). To ensure compatibility with subsequent signal standards, the signal is then converted from differential (LVDS) to single-ended (CMOS). The topological (TOPO) trigger [6] subsystem, originally crafted to enable the rejection of events based on the positions of the images in the cameras and relative position of the two MAGIC telescopes, was reprogrammed to enable coincidence of LST-1 L1 trigger signals with the L1 signals of MAGIC-I and MAGIC-II. This reconfigured system was then deployed in the MAGIC CH. On the LST-1 side, no further changes are necessary, as the telescope camera, equipped with a Trigger Interface board (TIB) [7], is ready to receive L1 trigger signals from neighboring telescopes.

3. Performance estimation

Extensive Monte Carlo (MC) simulations underpin the expected performance of an IACT system. First, we provide a concise explanation of the MC simulations setup and the analysis pipeline used for the performance evaluation of the HaST system. We re-utilize the same MC simulation productions of gamma rays, along with background noise events such as protons and helium, and electrons as in [8]. The simulation from the emission of Cherenkov light to the instrumental response of MAGIC and LST-1 is performed with *CORSIKA* [9] and *sim_telarray* [10]. From the low-level information like the waveforms signals of each simulated PMT pixel, the `magic_cta_pipe` [1] was used to reconstruct high-level information such as the physical quantities of primary particles entering the atmosphere, including their arrival direction, energy, and particle species. Since the HaST approach allows us to capture **any-two** events that are triggered only by MAGIC-I and LST-1 or MAGIC-II and LST-1, which would be discarded by the software coincidence method, we kept these events until the final phase of the analysis.

The distribution of MC gamma-ray events incident from zd = 20 deg at the trigger level segregated by true energy is presented in Figure 3. Due to its extensive effective area, the majority of events across all energy bands are triggered by LST-1. Aside from LST-1-mono events, as the energy increases, brighter showers are more likely to form, resulting in an increase of LST-1+M1+M2 events. Conversely, at lower energies (< 0.12 TeV), roughly 1-2 times more LST-1+M1

---

[1] `https://github.com/cta-observatory/magic-cta-pipe`

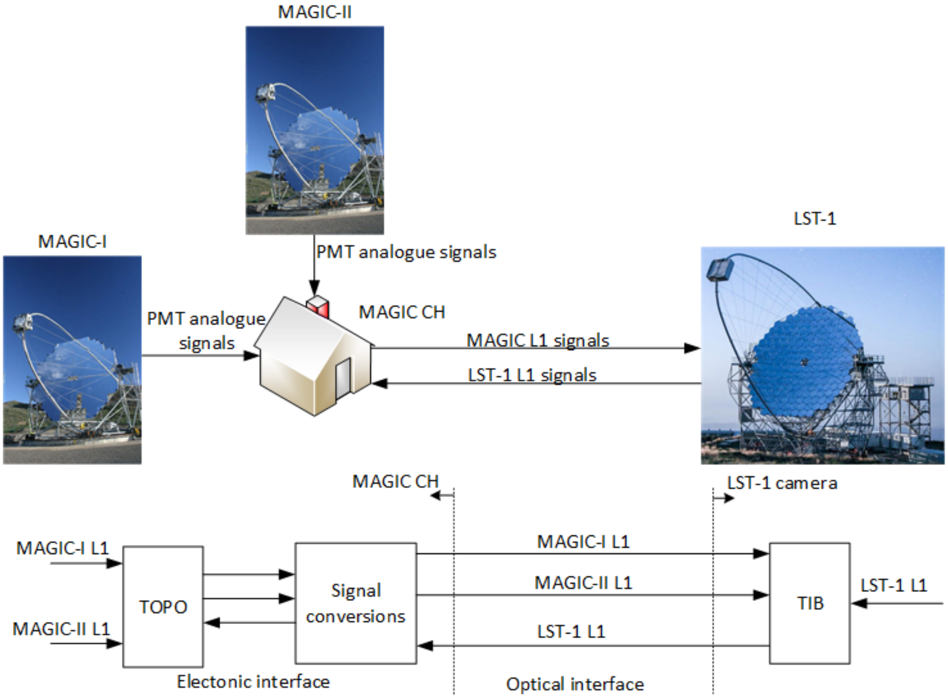

Figure 2: Overview of the HaST system. The upper part of the image shows the signals between the three telescopes and the MAGIC CH. Below, the main hardware subsystems involve in the HaST are shown.

events and 2-3 times more LST-1+M2 events are triggered compared to LST-1+M1+M2 events. The higher occurrence of LST-1+M2 events compared to LST-1+M1 events is attributed to their geometric proximity.

Subsequently, using MC gamma rays with zd < 30 deg, we estimated the energy thresholds for three different approaches; HaST-system approach, Software Coincidence (SC) approach, and MAGIC-only approach (Figure 4). MAGIC-only approach here refers to the method of mimicking the performance of the MAGIC by processing the events triggered by MAGIC stereo with `magic_cta_pipe`, without involving event information from LST-1. To enhance the production efficiency, MCs are initially generated with a spectral index of -2.0; however, when deriving the energy threshold from the event distribution, they are reweighted to a spectral index of -2.6, which resembles that of the standard gamma-ray candle, the Crab Nebula. The respective energy thresholds are estimated to be $\sim$ 39 GeV for HaST, $\sim$ 49 GeV for SC, and $\sim$ 56 GeV for MAGIC-only, namely, HaST system presents an improvement of about 20% over SC, and roughly 30% over MAGIC-only. The ratio of triggered events clearly shows the effect of effective area expansion by the HaST system, as seen in the fact that the HaST system increases the number of triggered events by another 3-4 times more than the SC method, which itself enhances the event count by up to twice that achieved solely with MAGIC.

Lastly, we estimated the sensitivity based on the widely used definition for steady point source observations in the IACT community [2]. Specifically, we assume an observation time of 50 hours

---

[2] For example, see [4]

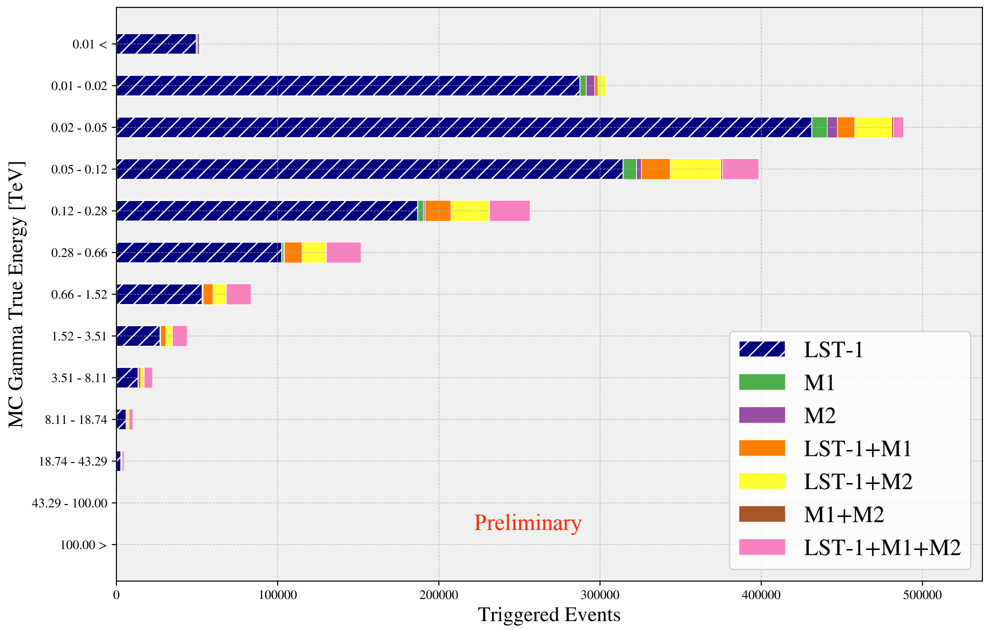

Figure 3: MC gamma-rays true energy distribution of events by telescope triggered. For example, LST-1 + M2 represents events triggered by LST-1 and MAGIC-II (M2) but not by MAGIC-I (M1).

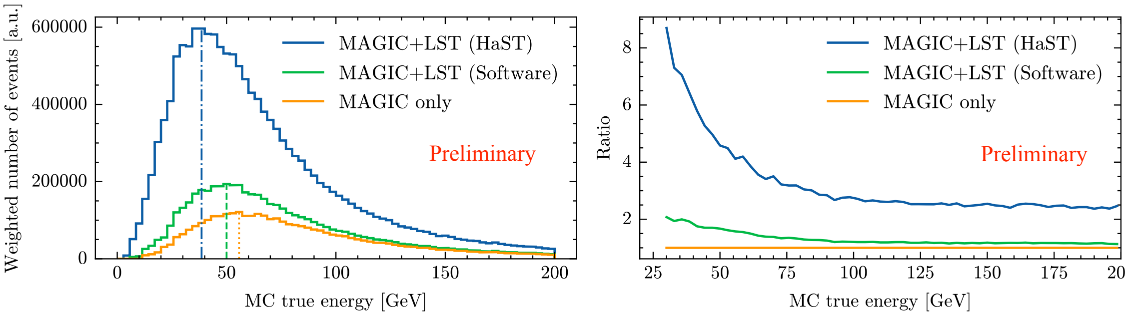

Figure 4: *Left*: the distribution of the true energy derived from MC simulations for gamma rays at zd < 30 deg, reweighted for a source spectral index of -2.6. MAGIC+LST events by the HaST system is colored blue, MAGIC+LST events by the Software-Coincidence (SC) approach is green, and MAGIC-only events is orange. The dotted line indicates the peak of the distribution, i.e., the energy threshold of the corresponding system. *Right*: The ratio of the number of events over MAGIC-only events.

and divide the dataset into 5 bins per decade in reconstructed energy. We then seek the minimal flux that satisfies a trifold criteria: (1) detection of more than 10 events attributed to gamma rays, (2) a S/N surpassing 5 %, and (3) Li&Ma significance [11] exceeds 5σ. To avoid bias in the selection of the dataset during cut optimization, we divided the dataset into four subsamples and conducted k-fold cross-validation. The result of our estimation is given in Figure 5. The improvements in the effective area and energy threshold provided by the HaST system result in a overall sensitivity enhancement of more than 1.1 times against the software-coincidence method across the majority of energy bands. Particularly in the lowest energies ($\lesssim$ 100 GeV), both sensitivity of HaST system demonstrate a improvement of about 1.1 to 1.5 times, indicating that the HaST system contributes to the performance boost in the lowest energy band. On the other hand, given the scarcity of statistic in the highest energies, generating an accurate estimate with the present production poses a challenge, marking it as an area for future investigation.

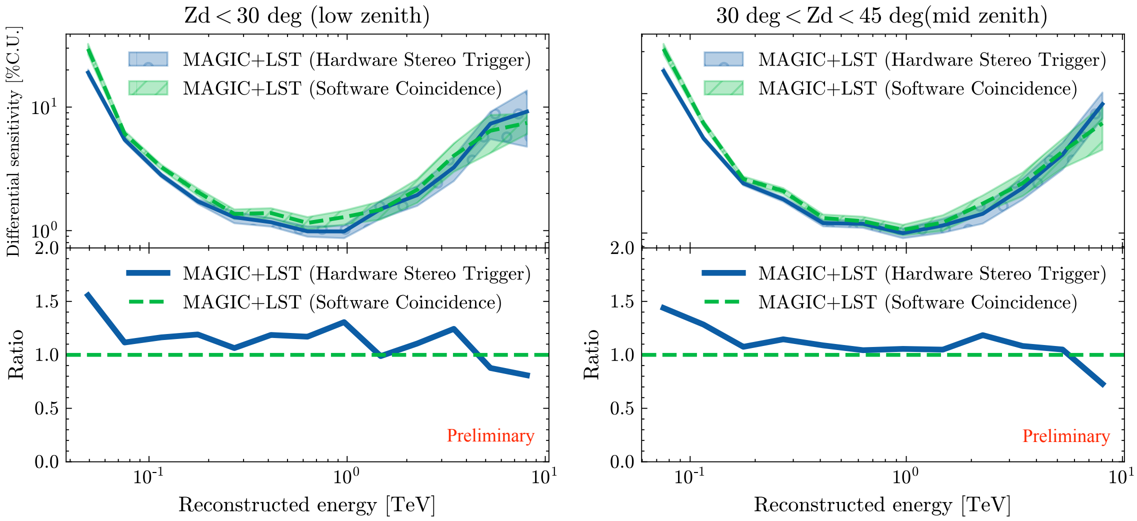

Figure 5: Differential sensitivity in Crab flux Unit (%C.U.) based on low zd (zd < 30 deg) and mid zd (30 deg < zd < 45 deg) MC simulations for a 50 hour observation of a steady point source. The above curves compare the sensitivity of the HaST system, which handles events triggered by any-two or more telescopes, with the sensitivity of the Software-Coincidence method, which deals with events triggered by all three telescopes. Below the each plot, the mean ratio of the HaST system's sensitivity to that of the Software Coincidence is given.

4. Conclusion and Outlook

We have reported on the current status of the HaST system's implementation between MAGIC and LST-1, and its expected performance using Monte Carlo simulations. The introduction of the HaST system has made it possible to record events triggered between any-two of the three telescopes, which was previously unattainable with the offline joint analysis methods. We showed that the system contributes to lowering the energy threshold, further improving the sensitivity of the IACT system.

We have recently conducted test observations of the HaST system by pointing the telescopes towards known galactic and extragalactic sources, including the Crab Nebula. The data obtained from the observations are currently being analyzed. The amplification of triggered events as expected in the MC study has actually been confirmed. Once the optimization of the system is completed through commissioning, joint observations by MAGIC and LST-1 using the HaST system are expected to become feasible within this year. Moreover, through the additional integration of the optical fiber cables, coupled with a envisaged firmware/software updates, the HaST methodology could potentially enable the joint observations amongst the forthcoming LST-2, 3, 4, and MAGIC.

LST Acknowledgements

We gratefully acknowledge financial support from the following agencies and organisations:

Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Fundação de Apoio à Ciência, Tecnologia e Inovação do Paraná - Fundação Araucária, Ministry of Science, Technology, Innovations and Communications (MCTIC), Brasil; Ministry of Education and Science, National RI Roadmap Project DO1-153/28.08.2018, Bulgaria; Croatian Science Foundation, Rudjer Boskovic Institute, University of Osijek, University of Rijeka, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Zagreb, Faculty of Electrical Engineering and Computing, Croatia; Ministry of Education, Youth and Sports, MEYS LM2015046, LM2018105, LTT17006, EU/MEYS CZ.02.1.01/0.0/0.0/16_013/0001403, CZ.02.1.01/0.0/0.0/18_046/0016007 and CZ.02.1.01/0.0/0.0/16_019/0000754, Czech Republic; CNRS-IN2P3, the French Programme d'investissements d'avenir and the Enigmass Labex, This work has been done thanks to the facilities offered by the Univ. Savoie Mont Blanc - CNRS/IN2P3 MUST computing center, France; Max Planck Society, German Bundesministerium für Bildung und Forschung (Verbundforschung / ErUM), Deutsche Forschungsgemeinschaft (SFBs 876 and 1491), Germany; Istituto Nazionale di Astrofisica (INAF), Istituto Nazionale di Fisica Nucleare (INFN), Italian Ministry for University and Research (MUR); ICRR, University of Tokyo, JSPS, MEXT, Japan; JST SPRING - JPMJSP2108; Narodowe Centrum Nauki, grant number 2019/34/E/ST9/00224, Poland; The Spanish groups acknowledge the Spanish Ministry of Science and Innovation and the Spanish Research State Agency (AEI) through the government budget lines PGE2021/28.06.000X.411.01, PGE2022/28.06.000X.411.01 and PGE2022/28.06.000X.711.04, and grants PGC2018-095512-B-I00, PID2019-104114RB-C31, PID2019-107847RB-C44, PID2019-104114RB-C32, PID2019-105510GB-C31, PID2019-104114RB-C33, PID2019-107847RB-C41, PID2019-107847RB-C43, PID2019-107988GB-C22; the "Centro de Excelencia Severo Ochoa" program through grants no. CEX2021-001131-S, CEX2019-000920-S; the "Unidad de Excelencia María de Maeztu" program through grants no. CEX2019-000918-M, CEX2020-001058-M; the "Juan de la Cierva-Incorporación" program through grant no. IJC2019-040315-I. They also acknowledge the the "Programa Operativo" FEDER 2014-2020, Consejería de Economía y Conocimiento de la Junta de Andalucía (Ref. 1257737), PAIDI 2020 (Ref. P18-FR-1580) and Universidad de Jaén; "Programa Operativo de Crecimiento Inteligente" FEDER 2014-2020 (Ref. ESFRI-2017-IAC-12), Ministerio de Ciencia e Innovación, 15% co-financed by Consejería de Economía, Industria, Comercio y Conocimiento del Gobierno de Canarias; the "CERCA" program of the Generalitat de Catalunya; and the European Union's "Horizon 2020" GA:824064 and NextGenerationEU; We acknowledge the Ramon y Cajal program through grant RYC-2020-028639-I and RYC-2017-22665; State Secretariat for Education, Research and Innovation (SERI) and Swiss National Science Foundation (SNSF), Switzerland; The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreements No 262053 and No 317446; This project is receiving funding from the European Union's Horizon 2020 research and innovation programs under agreement No 676134; ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

MAGIC Acknowledgements

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The financial support of the German BMBF, MPG and HGF; the Italian INFN and INAF; the Swiss National Fund SNF; the ERDF under the Spanish Ministerio de Ciencia e Innovación (MICINN) (PID2019-104114RB-C31, PID2019-104114RB-C32, PID2019-104114RB-C33, PID2019-105510GB-C31,PID2019-107847RB-C41, PID2019-107847RB-C42, PID2019-107847RB-C44, PID2019-107988GB-C22); the Indian Department of Atomic Energy; the Japanese ICRR, the University of Tokyo, JSPS, and MEXT; the Bulgarian Ministry of Education and Science, National RI Roadmap Project DO1-400/18.12.2020 and the Academy of Finland grant nr. 320045 is gratefully acknowledged. This work was also supported by the Spanish Centro de Excelencia "Severo Ochoa" (SEV-2016-0588, SEV-2017-0709, CEX2019-000920-S), the Unidad de Excelencia "María de Maeztu" (CEX2019-000918-M, MDM-2015-0509-18-2) and by the CERCA program of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2016-06-9782 and the University of Rijeka Project 13.12.1.3.02; by the DFG Collaborative Research Centers SFB823/C4 and SFB876/C3; the Polish National Research Centre grant UMO-2016/22/M/ST9/00382; and by the Brazilian MCTIC, CNPq and FAPERJ.

References

[1] B. S Acharya et al., Astroparticle Physics, 43:3–18, March 2013.

[2] CTA Consortium and B. S. Acharya et al., Astroparticle Physics 111, 35.

[3] CTA-LST Project (2023), https://doi.org/10.48550/arXiv.2306.12960

[4] J. Aleksić et al., Astroparticle Physics, 72:76–94, jan 2016.

[5] F. Dazzi et al., in IEEE Transactions on Nuclear Science, 68, 7, 1473-1486, July 2021.

[6] R. López-Coto et al., Journal of Instrumentation, 11,4,P04005–P04005, 2016

[7] Luis A. Tejedor et al., Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166058.

[8] Federico Di Pierro et al, "Performance of joint observations with MAGIC and LST-1", in these proceedings, https://pos.sissa.it/444/

[9] D.Heck,et al., CORSIKA:a Monte Carlo code to simulate extensive airshowers, Tech. Rep. FZKA 6019, Forschungszentrum Karlsruhe, (1998)

[10] K.Bernlöhr, Astroparticle Physics 30 (2008) 149.

[11] T. Li et al. The Astrophysical Jornal, 272:317-324, 1983, Sep 1983.

Full Author List: The CTA LST Project and the MAGIC Collaboration

H. Abe[1], K. Abe[2], S. Abe[1], J. Abhir[3], V. A. Acciari[4], A. Aguasca-Cabot[5], I. Agudo[6], N. Alvarez Crespo[7], T. Aniello[8], S. Ansoldi[9,10], L. A. Antonelli[11], C. Aramo[12], A. Arbet-Engels[13], A. Cornelia[14], M. Artero[15], K. Asano[1], P. Aubert[16], D. Baack[17], A. Babić[18], A. Baktash[19], A. Bamba[20], A. Baquero Larriva[7,21], L. Baroncelli[22], U. Barres de Almeida[23], J. A. Barrio[7], I. Batkovic[14], J. Baxter[1], J. Becerra González[4], W. Bednarek[24], E. Bernardini[14], M. I. Bernardos[6], J. Bernete Medrano[25], A. Berti[13], J. Besenrieder[13], P. Bhattacharjee[16], N. Biederbeck[17], C. Bigongiari[11], A. Biland[3], E. Bissaldi[26], O. Blanch[15], G. Bonnoli[27], P. Bordas[5], Ž. Bošnjak[18], A. Bulgarelli[22], I. Burelli[9], L. Burmistrov[28], M. Buscemi[29], G. Busetto[14], A. Campoy-Ordaz[30], M. Cardillo[31], S. Caroff[16], A. Carosi[11], R. Carosi[32], M. S. Carrasco[33], M. Carretero-Castrillo[5], F. Cassol[33], A. J. Castro-Tirado[6], D. Cauz[9], D. Cerasole[34], G. Ceribella[13], Y. Chai[13], K. Cheng[1], A. Chiavassa[35], M. Chikawa[1], A. Chilingarian[36], L. Chytka[37], A. Cifuentes[25], S. Cikota[18], E. Colombo[4], J. L. Contreras[7], J. Cortina[25], H. Costantini[33], S. Covino[8], G. D'Amico[38], M. Dalchenko[28], V. D'Elia[8], P. Da Vela[32,39], F. Dazzi[11], A. De Angelis[14], M. de Bony de Lavergne[16], B. De Lotto[9], M. De Lucia[12], R. de Menezes[35], L. Del Peral[40], G. Deleglise[16], M. Delfino[15,41], C. Delgado[25], J. Delgado Mengual[41], D. della Volpe[28], M. Dellaiera[16], A. Del Popolo[29], D. Depaoli[35,42], A. Di Piano[22], F. Di Pierro[35], A. Di Pilato[28], R. Di Tria[34], L. Di Venere[34], C. Díaz[25], R. M. Dominik[17], D. Dominis Prester[43], A. Donini[11], D. Dorner[44], M. Doro[14], L. Eisenberger[44], D. Elsässer[17], G. Emery[45,33], J. Escudero[6], V. Fallah Ramazani[46], L. Fariña[15], A. Fattorini[17], G. Ferrara[29], F. Ferrarotto[47], A. Fiasson[16,48], L. Foffano[31], L. Font[30], L. Freixas Coromina[25], S. Fröse[17], S. Fukami[1,3], Y. Fukazawa[49], E. Garcia[16], R. Garcia López[4], M. Garczarczyk[50], C. Gasbarra[51], D. Gasparrini[51], S. Gasparyan[52], M. Gaug[30], D. Geyer[17], J. Giesbrecht Paiva[23], N. Giglietto[26], F. Giordano[34], P. Gliwny[24], N. Godinovic[53], R. Grau[15], J. Green[13], D. Green[13], S. Gunji[54], P. Günther[44], J. Hackfeld[46], D. Hadasch[1], A. Hahn[13], K. Hashiyama[1], T. Hassan[25], K. Hayashi[1], L. Heckmann[13], M. Heller[28], J. Herrera Llorente[4], K. Hirotani[1], D. Hoffmann[33], D. Horns[19], J. Houles[33], M. Hrabovsky[37], D. Hrupec[55], D. Hui[1], M. Hütten[1], M. Iarlori[56], R. Imazawa[49], T. Inada[1], Y. Inome[1], K. Ioka[57], M. Iori[47], R. Iotov[44], K. Ishio[24], I. Jimenez Martinez[25], J. Jormanainen[58], J. Jurysek[59], M. Kagaya[1], V. Karas[60], H. Katagiri[61], J. Kataoka[62], D. Kerszberg[15], G. W. Kluge[38,63], Y. Kobayashi[1], K. Kohri[64], A. Kong[1], P. M. Kouch[58], H. Kubo[1], J. Kushida[2], M. Lainez[7], G. Lamanna[16], A. Lamastra[11], T. Le Flour[16], D. Lelas[53], F. Leone[8], E. Lindfors[58], L. Linhoff[17], M. Linhoff[17], S. Lombardi[8], F. Longo[65], R. López-Coto[6], M. López-Moya[7], A. López-Oramas[4], S. Loporchio[34], A. Lorini[66], J. Lozano Bahilo[40], P. L. Luque-Escamilla[67], E. Lyard[45], B. Machado de Oliveira Fraga[23], P. Majumdar[68,1], M. Makariev[69], D. Mandat[59], G. Maneva[69], N. Mang[17], M. Manganaro[43], S. Mangano[25], G. Manicò[29], K. Mannheim[44], M. Mariotti[14], P. Marquez[15], G. Marsella[29,70], J. Martí[67], O. Martinez[71], G. Martínez[25], M. Martínez[15], M. Martínez-Chicharro[25], A. Mas-Aguilar[7], G. Maurin[16], D. Mazin[1,13], S. Menchiari[66], S. Mender[17], E. Mestre Guillen[67], S. Micanovic[43], D. Miceli[14], T. Miener[7], J. M. Miranda[71,66], R. Mirzoyan[13], T. Mizuno[72], M. Molero Gonzalez[4], E. Molina[5], H. A. Mondal[68], T. Montaruli[28], I. Monteiro[16], A. Moralejo[15], D. Morcuende[7], A. Morselli[51], V. Moya[7], H. Muraishi[73], K. Murase[1], S. Nagataki[74], T. Nakamori[54], C. Nanci[8], L. Nava[8], A. Neronov[75], V. Neustroev[76], L. Nickel[17], M. Nievas Rosillo[4], C. Nigro[15], L. Nikolić[66], K. Nilsson[58], K. Nishijima[2], T. Njoh Ekoume[4], K. Noda[1], D. Nosek[77], S. Nozaki[13], M. Ohishi[1], Y. Ohtani[1], T. Oka[78], A. Okumura[79,80], R. Orito[81], J. Otero-Santos[4], S. Paiano[8], M. Palatiello[9], D. Paneque[13], F. R. Pantaleo[26], R. Paoletti[66], J. M. Paredes[5], L. Pavletić[43], D. Pavlović[43], M. Pech[59,0], M. Pecimotika[43], M. Peresano[35], M. Persic[9,8], F. Pfeiffle[44], E. Pietropaolo[82], M. Pihet[14], G. Pirola[13], C. Plard[16], F. Podobnik[66], V. Poireau[16], M. Polo[25], E. Pons[16], P. G. Prada Moroni[32], E. Prandini[14], J. Prast[16], G. Principe[65], C. Priyadarshi[15], M. Prouza[59], R. Rando[14], W. Rhode[17], M. Ribó[5], J. Rico[15], C. Righi[27], V. Rizi[82], G. Rodriguez Fernandez[51], M. D. Rodríguez Frías[40], N. Sahakyan[52], T. Saito[1], S. Sakurai[1], D. A. Sanchez[16], T. Šarić[53], K. Satalecka[58], Y. Sato[83], F. G. Saturni[11], V. Savchenko[75], B. Schleicher[44], K. Schmidt[17], F. Schmuckermaier[13], J. L. Schubert[17], F. Schussler[84], T. Schweizer[13], A. Sciaccaluga[8], M. Sato[16], T. Siegert[44], R. Silvia[34], J. Sitarek[24], V. Sliusar[45], D. Sobczynska[24], A. Spolon[14], A. Stamerra[8], J. Strišković[55], D. Strom[13], M. Strzys[1], Y. Suda[49], T. Surić[85], S. Suutarinen[58], H. Tajima[79], M. Takahashi[79], H. Takahashi[49], J. Takata[1], R. Takeishi[1], P. H. T. Tam[1], S. J. Tanaka[83], D. Tateishi[86], F. Tavecchio[8], P. Temnikov[69], Y. Terada[86], K. Terauchi[78], T. Terzic[43], M. Teshima[13,1], M. Tluczykont[19], F. Tokanai[54], D. F. Torres[87], L. Tosti[88], P. Travnicek[59], S. Truzzi[66], A. Tutone[11], S. Ubach[30], M. Vacula[37], P. Vallania[35], J. van Scherpenberg[13], M. Vázquez Acosta[4], S. Ventura[66], V. Verguilov[69], I. Viale[14], A. Vigliano[9], C. F. Vigorito[35,42], V. Vitale[51], G. Voutsinas[28], I. Vovk[1], T. Vuillaume[16], R. Walter[45], Z. Wei[87], M. Will[13], C. Wunderlich[66], T. Yamamoto[89], R. Yamazaki[83], T. Yoshida[61], T. Yoshikoshi[1], N. Zywucka[24]

[1]Institute for Cosmic Ray Research, University of Tokyo. [2]Department of Physics, Tokai University. [3]ETH Zürich. [4]Instituto de Astrofísica de Canarias and Departamento de Astrofísica, Universidad de La Laguna. [5]Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB. [6]Instituto de Astrofísica de Andalucía-CSIC. [7]EMFTEL department and IPARCOS, Universidad Complutense de Madrid. [8]National Institute for Astrophysics (INAF). [9]INFN Sezione di Trieste and Università degli Studi di Udine. [10]International Center for Relativistic Astrophysics (ICRA). [11]INAF - Osservatorio Astronomico di Roma. [12]INFN Sezione di Napoli. [13]Max-Planck-Institut für Physik. [14]INFN Sezione di Padova and Università degli Studi di Padova. [15]Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology. [16]LAPP, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS-IN2P3, Annecy. [17]Department of Physics, TU Dortmund University. [18]University of Zagreb, Faculty of Electrical Engineering and Computing (FER). [19]Universität Hamburg, Institut für Experimentalphysik. [20]Graduate School of Science, University of Tokyo. [21]Universidad del Azuay. [22]INAF - Osservatorio di Astrofisica e Scienza dello spazio di Bologna. [23]Centro Brasileiro de Pesquisas Físicas. [24]Faculty of Physics and Applied Informatics, University of Lodz. [25]CIEMAT. [26]INFN Sezione di Bari and Politecnico di Bari. [27]INAF - Osservatorio Astronomico di Brera. [28]University of Geneva - Département de physique nucléaire et corpusculaire. [29]INFN Sezione di Catania. [30]Departament de Física, and CERES-IEEC, Universitat Autónoma de Barcelona. [31]INAF - Istituto di Astrofisica e Planetologia Spaziali (IAPS). [32]Università di Pisa and INFN Pisa. [33]Aix Marseille Univ, CNRS/IN2P3, CPPM. [34]INFN Sezione di Bari and Università di Bari. [35]INFN Sezione di Torino. [36]ICRANet-Armenia at NAS RA. [37]Palacky University Olomouc, Faculty of Science. [38]>Department for Physics and Technology, University of Bergen. [39]University of Innsbruck. [40]University of Alcalá UAH. [41]Port d'Informació Científica. [42]Dipartimento di Fisica - Universitá degli Studi di Torino. [43]University of Rijeka, Department of Physics. [44]Institute for Theoretical Physics and Astrophysics, Universität Würzburg. [45]Department of Astronomy, University of Geneva. [46]Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum. [47]INFN Sezione di Roma La Sapienza. [48]ILANCE, CNRS . [49]Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University. [50]Deutsches Elektronen-Synchrotron (DESY). [51]INFN Sezione di Roma Tor Vergata. [52]A. Alikhanyan National Science Laboratory. [53]University of Split, FESB. [54]Department of Physics, Yamagata University. [55]Josip Juraj Strossmayer University of Osijek, Department of Physics. [56]INFN Dipartimento di Scienze Fisiche e Chimiche - Università degli Studi dell'Aquila and Gran Sasso Science Institute. [57]Yukawa Institute for Theoretical Physics, Kyoto University. [58]Finnish Centre for Astronomy with ESO, University of Turku. [59]FZU - Institute of Physics of the Czech Academy of Sciences. [60]Astronomical Institute of the Czech Academy of Sciences. [61]Faculty of Science, Ibaraki University. [62]Faculty of Science and Engineering, Waseda University. [63]Department of Physics, University of Oslo. [64]Institute of Particle and Nuclear Studies, KEK (High Energy Accelerator Research Organization). [65]INFN Sezione di Trieste and Università degli Studi di Trieste. [66]INFN and Università degli Studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente (DSFTA). [67]Escuela Politécnica Superior de Jaén, Universidad de Jaén. [68]Saha Institute of Nuclear Physics. [69]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences. [70]Dipartimento di Fisica e Chimica 'E. Segrè' Università degli Studi di Palermo. [71]Grupo de Electronica, Universidad Complutense de Madrid. [72]Hiroshima Astrophysical Science Center, Hiroshima University. [73]School of Allied Health Sciences, Kitasato University. [74]RIKEN, Institute of Physical and Chemical Research. [75]Laboratory for High Energy Physics, École Polytechnique Fédérale. [76]Astronomy Research Unit, University of Oulu. [77]Charles University, Institute of Particle and Nuclear Physics. [78]Division of Physics and Astronomy, Graduate School of Science, Kyoto University. [79]Institute for Space-Earth Environmental Research, Nagoya University. [80]Kobayashi-Maskawa Institute (KMI) for the Origin of Particles and the Universe, Nagoya University. [81]Graduate School of Technology, Industrial and Social Sciences, Tokushima University. [82]INFN Dipartimento di Scienze Fisiche e Chimiche - Università degli Studi dell'Aquila and Gran Sasso Science Institute. [83]Department of Physical Sciences, Aoyama Gakuin University. [84]IRFU, CEA, Université Paris-Saclay. [85]Ruđer Bošković Institute. [86]Graduate School of Science and Engineering, Saitama University. [87]Institute of Space Sciences (ICE-CSIC), and Institut d'Estudis Espacials de Catalunya (IEEC), and Institució Catalana de Recerca I Estudis Avançats (ICREA). [88]INFN Sezione di Perugia. [89]Department of Physics, Konan University.