PROCEEDINGS OF SCIENCE

PoS(ICRC2023)636

Performance of joint gamma-ray observations with MAGIC and LST-1 telescopes

F. Di Pierro,[a,*] A. Berti,[b] R. de Menezes,[a,c] E. Jobst,[b] Y. Ohtani,[d] J. Sitarek,[e] Y. Suda[f] and E. Visentin[a,c] for the CTA-LST project and the MAGIC collaboration

[a] *INFN Torino,*
Via P. Giuria 1, Torino, Italy
[b] *Max-Planck-Institut für Physik,*
Föhringer Ring 6, München, Germany
[c] *Università degli Studi di Torino, Dipartimento di Fisica,*
Via P. Giuria 1, Torino, Italy
[d] *University of Tokyo, Institute for Cosmic Ray Research,*
5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan
[e] *University of Lodz, Faculty of Physics and Applied Informatics,*
ul. Pomorska 149-153, Lodz, Poland
[f] *Hiroshima University, Physics Program, Graduate School of Advanced Science and Engineering,*
739-8526 Hiroshima, Japan

E-mail: federico.dipierro@to.infn.it

The prototype Large-Sized Telescope (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) is in commissioning phase at the Observatorio del Roque de Los Muchachos at 2200 m a.s.l. in La Palma (Canary Islands, Spain). LST-1 is a 23-m diameter telescope and is the first of four that will compose the LST part of the CTAO Northern array. The LST subarray is optimized to provide the best sensitivity for gamma rays in the 20 GeV - 200 GeV energy range. The MAGIC telescopes, which are located approximately 100 m from the LST-1, is operating as a two 17-m telescope stereoscopic system for more than 14 years. LST-1 and MAGIC routinely perform joint observations of gamma-ray sources to exploit the potential of the three-telescope system. This contribution describes the analysis pipeline and evaluates the performance of the system using Monte Carlo simulations and data on the Crab Nebula. The sensitivity achieved during joint observations with MAGIC and LST-1 is about 30% higher than that of MAGIC alone.

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

---

[*] Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons
Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction

The study of very-high-energy ($\gtrsim$ 100 GeV) gamma rays is a unique tool to unveil the origin of cosmic rays and shade light on extremely energetic processes. The Cherenkov Telescope Array Observatory (CTAO) is the upcoming next-generation gamma-ray facility [1] composed of two telescope arrays located in each of Earth's hemispheres. In order to cover a broad energy range (from few tens of GeV up to a few hundreds of TeV) it will be composed of telescopes of three different sizes: Large-Sized Telescopes (LST), Medium-Sized Telescopes (MST) and Small-Sized Telescopes (SST). The LSTs, with mirror diameters of 23 m, will be the most sensitive to the lowest energy range of CTAO (tens of GeV). The construction of the first LST telescope, named LST-1, finished in October 2018 and since 2019 it is taking commissioning and engineering data [2].

LST-1 is located in Observatorio Roque de los Muchachos, La Palma (Spain), at the altitude of 2200 m a.s.l.. It is placed at a distance of only ~ 100 m from the MAGIC telescopes (Fig.1), a pair of 17 m diameter IACTs [3]. Both systems work independently, but accordingly to an MoU between the two collaborations they regularly perform joint observations of gamma-ray sources. An offline search of the same event seen by the two systems enables a joint LST-1+MAGIC analysis [4]. In this work we report the common analysis chain and the achieved performance, using both Monte Carlo (MC) simulations and observations of the Crab Nebula. This conference contribution summarizes results described in more details here [5].

2. MAGIC and LST-1

The main characteristics of the MAGIC telescopes and the LST-1 telescope are summarized in Table 1. In current scheme at trigger level the requirement is to have all three telescopes while at analysis level just two images are needed. The presence of LST-1 allows to recover 20% of the events that, considering only the MAGIC telescopes, would be discarded because only one image would survive the quality cut (image intensity > 50 p.e.), while thanks to the LST-1 image can be further processed. This results in a 15% lower energy threshold as shown in Fig.2.

	Diameter	Camera FoV	Pixel FoV	# pixels	Peak QE	Trigger	Event rate
LST-1	23 m	4.5°	0.1°	1855	41%	mono	$10^4\ \mathrm{s}^{-1}$
MAGIC I/II	17 m	3.5°	0.1°	1039	32-34%	stereo	$300\ \mathrm{s}^{-1}$

Table 1: Summary of main LST-1 and MAGIC telescopes parameters.

3. The joint analysis pipeline

To analyze the joint observations, we developed a python-based analysis pipeline, named `magic-cta-pipe`[1] (MCP), based on `lstchain` [6] and `ctapipe` [7] libraries. The MCP pipeline is composed of several scripts each one dedicated to a specific analysis step. The highest level analysis steps are done with scripts using methods from `pyirf` [8] and `gammapy` [9]. Concerning the analysis of real data, after the event matching based on event timestamps, the calibration step,

---

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

PoS(ICRC2023)636

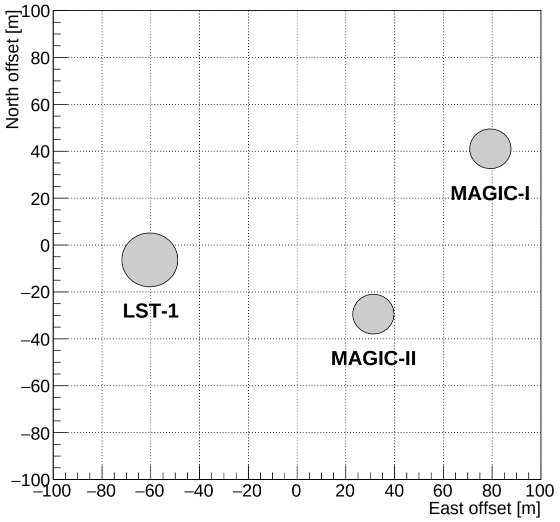

Figure 1: Positions of the LST-1 and MAGIC telescopes at Roque del Los Muchachos, La Palma. The diameter of the circle is proportional to the diameter of the telescope's mirror dish.

consisting in the extraction of the integrated charge in p.e. and the timing from the waveforms of each pixel, is done by `MARS` [10] for data from MAGIC and by `lstchain` for LST-1 data. Then the MAGIC data are converted into `HDF5` format, compatible with the LST-1 data using the dedicated `ctapipe_io_magic` package[2]. The standard image cleaning and Hillas image parameterization is applied to all calibrated images. Starting from the individual telescope parameters stereoscopic parameters are reconstructed, the shower axis, from which the *impact* parameter for each telescope and the *height of shower maximum*. Then telescope-wise distinct Random Forests (RF) [11] are used to reconstruct the energy, the arrival direction (by means of the DISP method [12]) and to classify the nature of the primary, through a classification parameter named *gammaness* [13]. The implementation of the RFs is done using the `scikit-learn` package [14]. The telescope-wise reconstructed parameters are averaged, weighting on image intensities, to get a single value for each parameter. Finally, to estimate higher level scientific products, such as the source spectral energy distribution (SED), the light curve (LC), the skymap; data should pass gamma-selection cuts based on *gammaness* and *theta* (i.e.: the angular distance between the reconstructed event and the known source position) and should be interpreted by means of the Instrument Response Functions obtained using MC test samples.

4. The datasets: Crab Nebula observations and Monte Carlo simulations

We estimated the performance of joint MAGIC+LST-1 observations using real observations of the Crab Nebula and from Monte Carlo simulations.

The observations used for the presented analysis have been performed between October 2020 and March 2021, with a final selection of 4 hours of good quality data, taken in the 12°-53° zenith angle range.

---

[2] `https://github.com/cta-observatory/ctapipe_io_magic`

PoS(ICRC2023)636

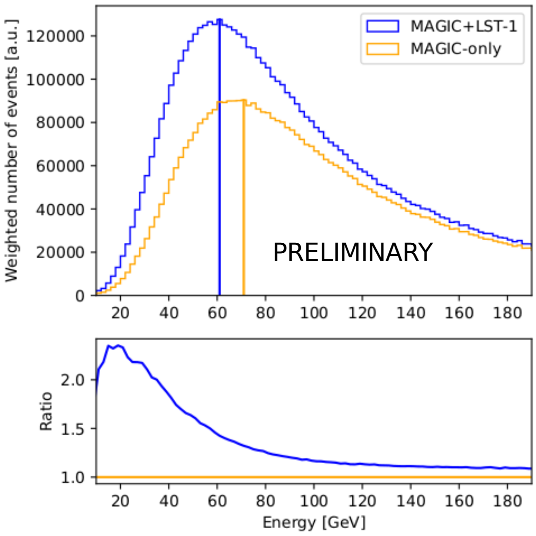

Figure 2: True energy distribution obtained with MC simulations (weighted to a source spectrum of −2.6) of gamma rays for $Zd < 30°$ at the reconstruction level (at least two images with *intensity* > 50). Vertical lines show the peak position for the joint analysis (blue) and MAGIC-only analysis (orange). Bottom panel shows the ratio of the two curves.

As described in the previous section, to analyze the real observations we have to rely on Monte Carlo samples. The basic MC samples to perform the analysis are gamma and proton primaries, in addition to them, electron and helium samples have been used to evaluate the sensitivity from simulations. The common simulation software used to simulate the response of all telescopes to the same EAS is `sim_telarray` [15], the standard simulation program for CTA. The validation of the MC has been done through comparison of distributions of intermediate reconstructed parameters obtained from real data and from simulations. The MAGIC telescope implementation in `sim_telarray` was further validated by a direct comparison with results obtained with the MAGIC collaboration's official simulation tool. As an end-to-end validation of the whole reconstruction process we report in Fig. 3 the energies reconstructed by the official MAGIC reconstruction + MC pipeline and our MCP + `sim_telarray` for the same real events.

In Fig. 4 the pointings of the real observations and of the training and test MC samples are reported. The MC training samples, simulated along the declination line of the source, are used to train the RFs. The MC test samples are used to derive the IRFs and the optimal quality cuts to analyze each individual data run, using interpolation among the closest nodes.

5. Performance of the joint MAGIC+LST-1 observations

A typical and robust check of the quality of an instrument and of its data analysis is the reconstruction of the spectrum of the Crab Nebula, commonly referred to as the standard candle of VHE gamma-rays. The Crab Nebula spectral energy distribution measured by MAGIC+LST-1, using 4h of data, taken mostly at medium zenith angles is shown in Fig. 5. The main applied image cuts are on intensity > 50 p.e. (MAGIC) and > 80 p.e. (LST-1), while the values of the

PoS(ICRC2023)636

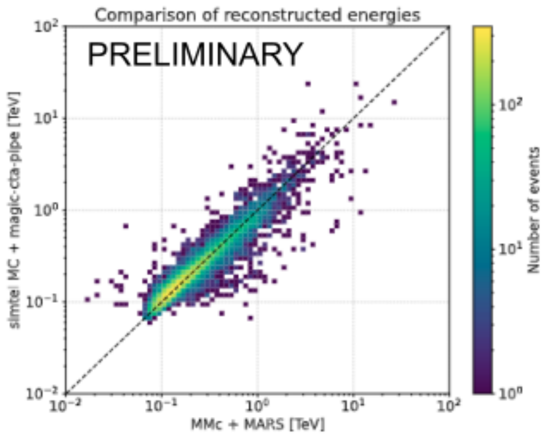

Figure 3: Comparison of the reconstructed energy of the same MAGIC-only events by MARS and MCP chain. Only gamma-like events with MARS hadronness value of < 0.2 and intensity of each image above 100 p.e. are used.

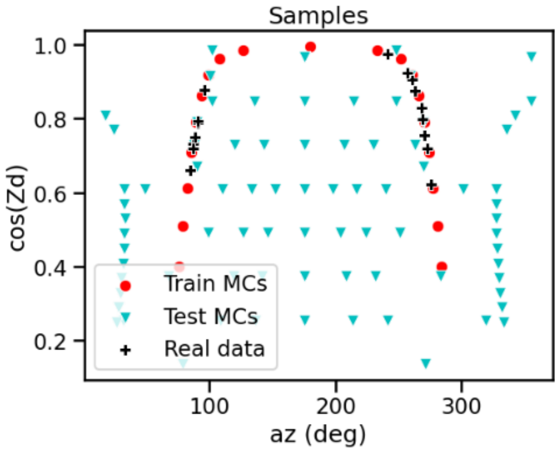

Figure 4: Simulated (Train and Test sample) and real data used in this analysis.

PoS(ICRC2023)636

energy dependent *gammaness* and *theta* cuts are obtained requiring a 90% gamma efficiency for the former and 80% containment radius for the latter. The obtained SED is compatible with previous mesurements by MAGIC reported in literature.

Comparing the reconstructed and the true energy of the MC samples it is possible to estimate the energy bias and resolution, defined as the mean of the $\frac{E_{true}-E_{rec}}{E_{true}}$ and the interval corresponding to 68% containment, respectively. Results are shown in Fig.6.

The angular resolution, defined as the angular distance from the source that corresponds to 68% containment of the point spread function, has been estimated using MC and Crab Nebula observations, applying the standard 90% efficiency cut in *gammaness*. Results, shown in Fig.7 for low and medium zenith angle, show a good agreement between MC and real data. At high energy (E >10 TeV) events far from the telescopes are included in the sample introducing an expected overall worsening of the angular resolution.

We finally show in Fig. 8 the estimated differential sensitivity of the MAGIC+LST-1 system,

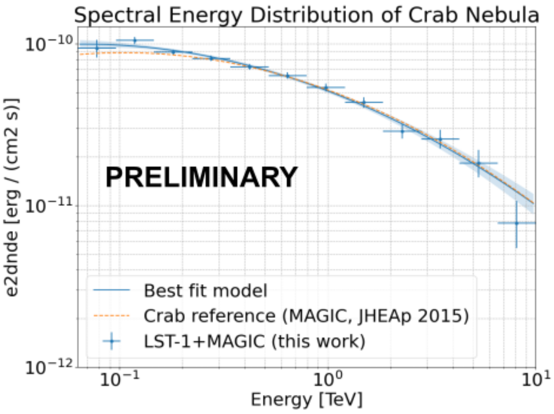

Figure 5: Spectral energy distribution of Crab Nebula obtained with joint LST-1+MAGIC observations compared to reference measurement from MAGIC-alone [16]).

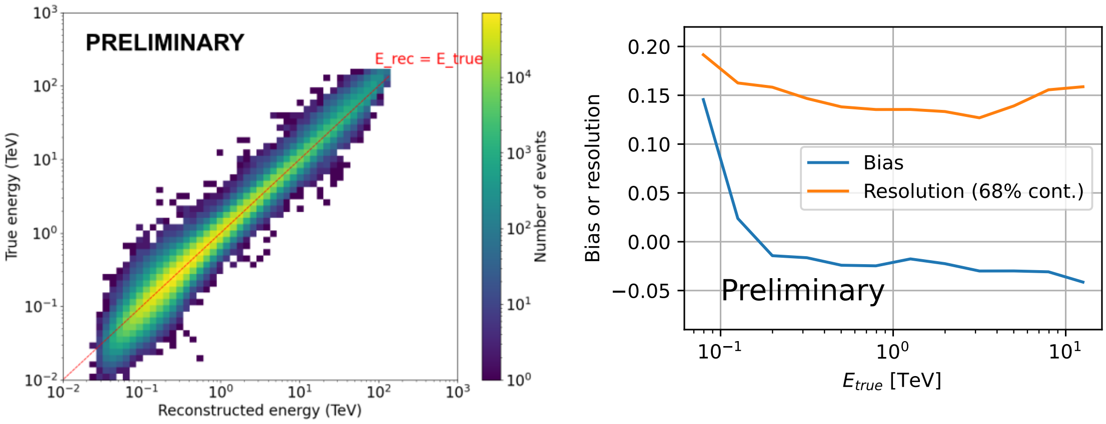

Figure 6: Left panel: Energy migration matrix, reconstructed energy vs true energy. Right panel: Energy bias and resolution.

from real Crab Nebula observations (blue) and from MC simulations (orange), compared to the MAGIC sensitivity estimated on the same data sample with the standard MAGIC analysis. We notice a rather good agreement between data and MC results, with still some discrepancies for E >1 TeV that should be further investigated and will probably require an improvement of the telescope models in MC. The improvement in sensitivity of the MAGIC+LST-1 joint observations is of the order of 30% with respect to MAGIC only observations.

6. Conclusions

Thanks to the proximity of LST-1 and the MAGIC telescopes it is possible to perform joint observations of the same gamma-ray sources. We described how the events are first matched and then reconstructed. We have shown the good agreement between MC and real data and also the good agreement between the newly developed analysis pipeline and the standard MAGIC one. As a robust check we have shown that the Crab Nebula SED measured by the MAGIC+LST-1 system is in perfect agreement with measurements from other instruments. We have shown the achieved

PoS(ICRC2023)636

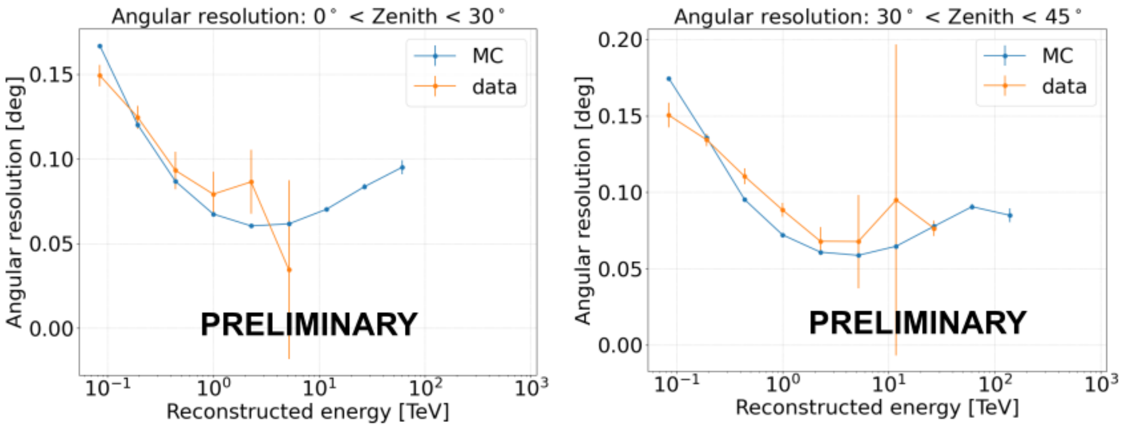

Figure 7: Angular resolution (68% containment radius), for low (left) and medium (right) zenith angles. Results for MC and Crab Nebula data are compared.

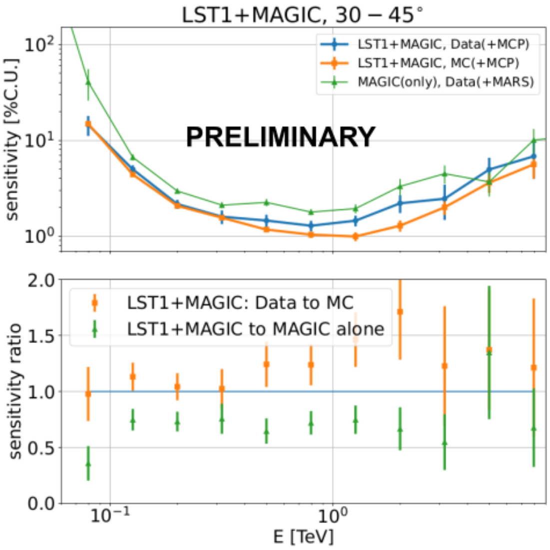

Figure 8: Differential sensitivity of the MAGIC+LST-1 joint observations. Estimation from Crab Nebula observations and MC are compared to MAGIC-only sensitivity estimated with the standard MAGIC analysis on real data.

angular and energy resolutions and an improvement in sensitivity of around 30% with respect to MAGIC only, making the three-telescopes system already a very powerful instrument.

References

[1] Acharya B. et al. 2013 Astroparticle Physics, 43, 3

[2] CTA-LST project 2021, Journal of Physics Conference Series, 2156, 012089. doi:10.1088/1742-6596/2156/1/012089

PoS(ICRC2023)636

[3] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2016a, Astroparticle Physics, 72, 61. doi:10.1016/j.astropartphys.2015.04.004

[4] Ohtani Y. et al. 2021 ICRC2021 Proceeding. doi:https://doi.org/10.22323/1.395.0724

[5] Sitarek J., Berti A., Di Pierro F., Ohtani Y., Suda Y., et al. 2023, submitted to A&A

[6] R. Lopez-Coto, T. Vuillaume, A. Moralejo et al. (2022) cta-observatory/cta-lstchain DOI 10.5281/zenodo.6344673.

[7] K. Kosack, M. Nöthe, J. Watson, et al., cta-observatory/ctapipe: (2022), DOI 10.5281/zenodo.3372210.

[8] Noethe, M., Kosack, K., Nickel, L., et al. 2022, 37th International Cosmic Ray Conference, 744. doi:10.22323/1.395.0744

[9] Deil, C., Zanin, R., Lefaucheur, J., et al. 2017, 35th International Cosmic Ray Conference (ICRC2017), 301, 766. doi:10.22323/1.301.0766

[10] Zanin R. et al., Proc of 33rd ICRC, Rio de Janeiro, Brazil, Id. 773, 2013

[11] Breiman, L. 2001, Machine Learning, 45, 5. doi:10.1023/A:1010933404324

[12] Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2010, A&A, 524, A77. doi:10.1051/0004-6361/201014747

[13] LST Collaboration et al. 2023 in prep

[14] Pedregosa, F., Varoquaux, G., Gramfort, A., et al. 2011, Journal of Machine Learning Research, 12, 2825. doi:10.48550/arXiv.1201.0490

[15] Bernlöhr, K. et al. 2013, Astroparticle Physics, 43, 171

[16] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015, Journal of High Energy Astrophysics, 5, 30. doi:10.1016/j.jheap.2015.01.002

PoS(ICRC2023)636

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[35,42], 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], E. Jobst[13], 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], E. Visentin[35,42], 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.

Acknowledgements We gratefully acknowledge financial support from the agencies and organizations listed here: *https://www.lst1.iac.es/acknowledgements.html*

PoS(ICRC2023)636