PROCEEDINGS OF SCIENCE

Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC

G. D'Amico,[a,*] I. Batković,[b] M. Doro[b] and M. Manganaro[c] on behalf of the MAGIC collaboration

[a] *Department for Physics and Technology, University of Bergen, Allégaten 55, Bergen, 5007, Norway*
[b] *University of Padova and INFN sez. Padova, via Marzolo 8, Padova, 35131, Italy*
[c] *Faculty of Physics, University of Rijeka, Radmile Matječić 2, Rijeka, 51000, Croatia*

E-mail: giacomo.damico@uib.no

Axion-like particles (ALPs) are pseudo-Nambu-Goldston bosons that appear in theories beyond the standard model and are capable of converting to photons in the presence of magnetic fields. Such interaction can have an observable effect on the gamma-ray spectrum of astrophysical targets. We have examined about 40 hours of observations made with the ground-based MAGIC Cherenkov telescopes in the direction of the Perseus Galaxy Cluster. The sources of VHE gamma rays present in the cluster and object of the study are the radiogalaxy NGC1275 and the HBL object IC310. These sources are bright in gamma rays and embedded in the cluster's high magnetic field, making them very good targets for this kind of study. Having not found statistical evidence for ALPs, we exclude ALPs models with masses in the sub-eV range in line with previous results. Last, we address the potential for gamma-ray-based instruments, both current and future, to identify ALP signals using this analysis technique, finding that the search for wiggles in TeV gamma-ray spectra is very unlikely to be sensitive enough for observations with IACTs.

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

*Speaker

PoS(ICRC2023)1442

1. Introduction

Axions are pseudo-Nambu-Goldstone bosons that emerge after the spontaneous breaking at a large energy scale f_a of a $U(1)$ symmetry, called Peccei-Quinn, originally introduced as a solution to the so-called Strong-CP problem [23] and further discussed in [27, 28]. The original Peccei-Quinn axion had a mass proportional to f_a at the eV scale (visible axion) and was soon experimentally discarded [14]. However, it was realized that axion-like particles (ALPs), similar to axions but lighter in mass, and having a mass independent on the coupling, arise in many theories beyond the Standard Model, from four-dimensional extensions of the Standard Model [26], to compactified Kaluza–Klein theories [15], and especially string theories [17, 24, 29], see, e.g.[13] for a review.

In this work we search for imprints of ALPs in the observed spectrum of two active galactic nuclei (AGNs) located in the Perseus GC: NGC 1275 and IC 310. Perseus is the brightest X-ray GC, displaying a dense population of electrons and a strong magnetic field at its core [16, 25]. It hosts two very bright TeV-emitting radio galaxies: NGC 1275 [5, 10–12] at its core, and the head-tail IC 310 [7] at 0.6 deg off-center. Both targets have been extensively sampled by MAGIC producing a wealth of scientific results especially because of their intense flaring activities. Further studies are found on the energy density at Perseus [8, 9] and more specific on and for dark matter [3].

From the observation with MAGIC of these two sources, we aim to place stringent constraints on the properties of ALPs, using a comprehensive model of the magnetic field and detailed statistical analysis to search for potential spectral indications of ALP-photon interaction.

2. Data Preparation and Signal Modeling

Our study in searching for ALP signatures is based on the photon survival probability

$$P^a_{\gamma\gamma} = P_{\gamma\to a\to\gamma}(\mathbf{B}, m_a, g_{a\gamma}), \tag{1}$$

defined as the probability that the photon initially emitted from the very-high-energy (VHE) gamma-ray source is converted to ALP and converted back to photon. This probability depends on the ALP mass m_a, the ALP-photon coupling $g_{a\gamma}$, and the ambient magnetic field intensity **B**. For its computation, we model the propagation using the `gammaALPs` open-source code[1] [21] which also includes the effects of the Extragalactic Background Light (EBL) and the modeling of magnetic fields. We model the optical depth due to EBL following Ref. [19]. While for the magnetic field of Perseus B^S, specific studies can be found in Refs. [16] and [25]. A recent comparison between magnetic field modeling in Perseus is also found in Ref. [18]. Parameters defined in `gammaALPs` for the magnetic field of Perseus are taken from Ref. [6] and summarized in Table 1.

	B_0 μG	η	n_0 cm^{-3}	n_2 cm^{-3}	$r_{\rm core}/r_{\rm core_2}$ kpc	β/β_2
B	10	0.5	$39 \cdot 10^{-3}$	$4.05 \cdot 10^{-3}$	80 / 280	1.2 / 0.58

Table 1: The parameters used for the modeling of the Perseus magnetic field from Ref. [6].

[1] https://github.com/me-manu/gammaALPs

For this study we selected the NGC 1275 data from the period of September 2016 to February 2017, corresponding to the period with highest flux from the source. The whole dataset of NGC 1275 includes ~ 40 hrs of data [12]. IC 310 was first detected in 2009 [7], and the dataset analyzed here includes ~ 2 hrs of data from one flaring state observed in Nov 2012. The data were processed with the MAGIC proprietary `MARS` analysis and reconstruction software [30] following the already published analysis [7, 10, 12]. We have converted the so-called MAGIC proprietary `melibea` files[2] into the so-called DL3 format. DL3 (Data Level 3) is the standard format adopted by the next-generation Cherenkov Telescope Array (CTA) consortium [4] as described in Ref. [22].

In Table 2 we report the total data used for this analysis and its division in 4 datasets, including the number of ON, OFF and *excess* (EXC) events for the four datasets, as well as the significance of the number of *excess* events computed, both for the individual datasets and a joined one, following Eq. 27 of Ref. [20]. In Table 2 we report the best fit SED parameters for the intrinsic energy spectrum, in agreement with [7, 12], which are taken to be a power law with an exponential cut-off (EPWL) for NGC 1275:

$$\phi^i_{int}(E') = \phi^i_0 \left(\frac{E'}{E_0}\right)^{\Gamma^i} e^{E'/E^i_k}, \tag{2}$$

for each i−th dataset of NGC 1275 and a power law (PWL) for IC 310:

$$\phi_{int}(E') = \phi_0 \left(\frac{E'}{E_0}\right)^{\Gamma}. \tag{3}$$

In both Equation 2 and Equation 3, E' is the reconstructed energy, ϕ_0 is the normalization flux computed at the energy scale E_0. Γ is the photon index, and E_k is the cutoff energy for the EPWL.

Target	Date	Duration [h]	N_{on}	N_{off}	N_{exc}	$\mathcal{S}_{\mathrm{Li\&Ma}}$
NGC 1275	1 Jan 17	2.5	6632	6703	4397	61.3
	02-03 Jan '17	2.8	4376	6060	2356	37.8
	Sep '16 - Feb '17	36.0	28830	68943	5849	31.8
IC 310	13 Nov '12	1.9	1469	2384	674	18.0
Sum		43.2	41307	84090	13276	63.0

Table 2: The four datasets used for the analysis. For each dataset we report the observation date, the duration in hours, the global number of events in the ON and OFF region (N_{on}, N_{off} respectively), and the significance of the excess signal in the dataset $\mathcal{S}_{\mathrm{Li\&Ma}}$.

3. Statistical Framework

Our statistical analysis is based on a likelihood maximization method. We firts define a binned likelihood as follows

$$\mathcal{L}(g_{a\gamma}, m_a, \mu|\mathbf{D}) = \prod_{i,k} \mathcal{L}_{i,k}(g_{a\gamma}, m_a, \mu_i|D_{i,k}) \tag{4}$$

[2]`melibea` files contain reconstructed stereo events information such as estimated energy, direction, and a classification parameter called *hadroness* h related to the likelihood of being a gamma-like event ($h \to 0$ for gamma-like candidates).

Target	Spectrum	Γ [cm^{-2}s^{-1}TeV^{-1}]	$\Phi_0/10^{-10}$ TeV	E_k
NGC 1275	EPWL	-2.31 ± 0.06	12.2 ± 1.0	0.72 ± 0.11
	EPWL	-1.79 ± 0.14	11.4 ± 2.1	0.29 ± 0.04
	EPWL	-2.54 ± 0.13	1.1 ± 0.2	0.5 ± 0.12
IC 310	PWL	-1.86 ± 0.04	1.8 ± 0.1	–

Table 3: The spectral features (assuming no ALP) for the 4 datasets considered in this study. EPWL stands for exponential cut-off power law (see Equation 2), while PWL for power-law (see Equation 3).

with the nuisance parameters μ_i for the i-th sample in our dataset and $D_{i,k} = (N_{\rm on}^{i,k}, N_{\rm off}^{i,k})$, the number of ON and OFF events observed in the k-th energy bin from the i-th sample (see Table 2). The likelihood is by definition the probability of observing the data $D_{i,k}$ assuming the model parameters $g_{a\gamma}$ and m_a to be true:

$$\mathcal{L}_{i,k} = \mathcal{P}\left(N_{\rm on}^{i,k} \mid s_{i,k} + \alpha b_{i,k}\right) \times \mathcal{P}\left(N_{\rm off}^{i,k} \mid b_{i,k}\right) \tag{5}$$

with $\mathcal{P}$ being the Poisson probability mass function for observing n counts with expected count rate r : $\mathcal{P}(n;r) = r^n e^{-r}/n!$. The parameter α is the exposure ratio of the ON and OFF region (see section 2), while $b_{i,k}$ and $s_{i,k}$ are the expected background and signal counts in the energy bin ΔE_k in the OFF region and ON region, respectively, for the i-th sample. The latter is obtained from

$$s_{i,k} = \int_{\Delta E_k} dE\ \phi^i_{obs}(E;\ g_{a\gamma}, m_a, \mu_i), \tag{6}$$

with

$$\phi^i_{obs} = \int dE' \phi^i_{int}(E';\mu_i) P_{\gamma\gamma}(E') \cdot \mathrm{IRF}^i(E|E'), \tag{7}$$

where $\mathrm{IRF}^i(E|E')$ is the instrument response function for the i-th sample, and $P_{\gamma\gamma}(E') = P^a_{\gamma\gamma}(E') \times P^{\rm EBL}_{\gamma\gamma}(E')$ is the survival probability in which both ALPs and EBL induced absorptions are taken into account. Given the likelihood in Equation 4, the statistic $\mathcal{S}$ is defined as:

$$\mathcal{S}(g_{a\gamma}, m_a) = -2\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(g_{a\gamma}, m_a, \hat{\mu}, \hat{\mathbf{B}}|\mathbf{D})}{\hat{\mathcal{L}}}, \tag{8}$$

where $\hat{\mathcal{L}}$ is the maximum value of the likelihood over the parameter space, while $\hat{\mu}$ and $\hat{\mathbf{B}}$ are obtained from profiling the likelihood, i.e. by fixing them to the values that maximize the likelihood for a given coupling $g_{a\gamma}$ and mass m_a. Lastly, to get exact coverage of the test statistic, we compute the distribution of $\mathcal{S}(g_{a\gamma}, m_a)$ for each of the 154 points considered in our analysis in the ALP parameter space $(g_{a\gamma}, m_a)$.

4. Results and Conclusions

We analyzed the 43 hrs of high-energy gamma-ray data coming from the direction of the Perseus galaxy cluster (see Table 2 and Table 3) in search for spectral irregularities induced by ALP in the sub-μeV mass range. Using a maximum likelihood analysis, as discussed in details

PoS(ICRC2023)1442

in section 3, we have tested the alternative hypothesis (presence of ALP) on 154 points regularly selected in the ALP parameter space. For each model we have computed the $P^a_{\gamma\gamma}$. The test statistic, once calibrated, does not provide a significant detection, which allowed us to compute 99% CL exclusion upper limits in the ALP parameter space. The excluded area match those by earlier results and to date these results offer the strongest constraints on ALP masses in the range of $40 - 90$ neV, with the greatest sensitivity for ALP masses of $m_a = 50$ neV, reaching the photon-ALP coupling down to $g_{a\gamma} = 2.0 \times 10^{-12}$ GeV^{-1}. Similar limits obtained with H.E.S.S. [2] or forecast with CTA [1] are also sensitive to lower ALP masses around 10 neV. We decided to further investigate this discrepancy. In particular, the results from the CTA were obtained by extrapolating a portion of the NGC 1275 dataset that we are using to generate this result: Ref. [1] consider that during the lifetime of CTA Perseus could be observed for 260 hrs, during which NGC 1275 would be in the baseline emission state for 250 hrs and in flaring state for 10 hrs. The authors model the baseline and flaring state with the values measured by MAGIC and reported here [7, 12]. We therefore adopt the same approach and recompute our limits as if we had taken 250 hrs of baseline and 10 hrs of flaring states. As done in [1], we neglect the post-flaring state of NGC 1275 and the emission from IC 310. To do so we are using the previously defined datasets where the observations are convoluted with the IRFs, ultimately giving us the predicted number of counts. To extend our flaring state and baseline to 10 hrs and 252 hrs respectively, we simulated with `gammapy` ~ 4 and ~ 7 times more total predicted counts in comparison to the original datasets of the flaring state and baseline used in the main part of this article. We observe that adding significantly more data allows to become sensitive to the parameter region with ALP masses around $1 - 10$ neV, in agreement with Ref. [1].

Author contributions

I.B. led the data and statistical analysis. G.D'A. led the statistical analysis and assisted in the interpretation of results. M.D. was in charge of project planning leading the interpretation of results and assisting in the data analysis. M.M. assisted in the data analysis and interpretation of results. The rest of the authors have contributed in one or several of the following ways: design, construction, maintenance and operation of the instrument(s); preparation and/or evaluation of the observation proposals; data acquisition, processing, calibration and/or reduction; production of analysis tools and/or related Monte Carlo simulations; discussion and approval of the contents of the draft.

Acknowledgments

I.B. and M.D. acknowledge funding from Italian Ministry of Education, University 362 and Research (MIUR) through the "Dipartimenti di eccellenza" project Science of the Universe. G.D'A's work on this project was supported by the Research Council of Norway, project number 301718. 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 grants PID2019-104114RB-C31, PID2019-104114RB-C32, PID2019-104114RB-C33, PID2019-105510GB-C31, PID2019-107847RB-C41, PID2019-107847RB-C42, PID2019-107847RB-C44, PID2019-107988GB-C22 funded by the Spanish MCIN/AEI/ 10.13039/501100011033; 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 been supported by Centros de Excelencia "Severo Ochoa" y Unidades "María de Maeztu" program of the Spanish MCIN/AEI/ 10.13039/501100011033 (SEV-2016-0588, CEX2019-000920-S, CEX2019-000918-M, CEX2021-001131-S, MDM-2015-0509-18-2) and by the CERCA institution of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2016-06-9782 and the University of Rijeka Project uniri-prirod-18-48; by the Deutsche Forschungsgemeinschaft (SFB1491 and SFB876); the Polish Ministry Of Education and Science grant No. 2021/WK/08; and by the Brazilian MCTIC, CNPq and FAPERJ.

References

[1] H. Abdalla et al. Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation. *JCAP*, 02:048, 2021.

[2] A. Abramowski et al. Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155-304 energy spectrum. *Phys. Rev. D*, 88(10):102003, 2013.

[3] V. A. Acciari et al. Constraining Dark Matter lifetime with a deep gamma-ray survey of the Perseus Galaxy Cluster with MAGIC. *Phys. Dark Univ.*, 22:38–47, 2018.

[4] B. S. Acharya et al. *Science with the Cherenkov Telescope Array*. WSP, 11 2018.

[5] M. L. Ahnen et al. Deep observation of the NGC 1275 region with MAGIC: search of diffuse γ-ray emission from cosmic rays in the Perseus cluster. *Astron. Astrophys.*, 589:A33, 2016.

[6] M. Ajello et al. Search for Spectral Irregularities due to Photon–Axionlike-Particle Oscillations with the Fermi Large Area Telescope. *Phys. Rev. Lett.*, 116(16):161101, 2016.

[7] J. Aleksic et al. Detection of very high energy gamma-ray emission from the Perseus cluster head-tail galaxy IC 310 by the MAGIC telescopes. *Astrophys. J. Lett.*, 723:L207, 2010.

[8] J. Aleksic et al. MAGIC Gamma-Ray Telescope Observation of the Perseus Cluster of Galaxies: Implications for Cosmic Rays, Dark Matter and NGC 1275. *Astrophys. J.*, 710:634–647, 2010.

[9] J. Aleksic et al. Constraining Cosmic Rays and Magnetic Fields in the Perseus Galaxy Cluster with TeV observations by the MAGIC telescopes. *Astron. Astrophys.*, 541:A99, 2012.

[10] J. Aleksic et al. Detection of very high energy gamma-ray emission from NGC 1275 by the MAGIC telescopes. *Astron. Astrophys.*, 539:L2, 2012.

[11] J. Aleksić et al. Contemporaneous observations of the radio galaxy NGC 1275 from radio to very high energy γ-rays. *Astron. Astrophys.*, 564:A5, 2014.

[12] S. Ansoldi et al. Gamma-ray flaring activity of NGC1275 in 2016–2017 measured by MAGIC. *Astron. Astrophys.*, 617:A91, 2018.

[13] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald. WISPy cold dark matter. *JCAP*, 2012(6):013, June 2012.

[14] Y. Asano, E. Kikutani, S. Kurokawa, T. Miyachi, M. Miyajima, Y. Nagashima, T. Shinkawa, S. Sugimoto, and Y. Yoshimura. Search for a rare decay mode $K^+ \to \pi^+ \nu$ overlinev and axion. *Phys. Lett. B*, 107(1-2):159–162, Dec. 1981.

[15] S. Chang, S. Tazawa, and M. Yamaguchi. Axion model in extra dimensions with TeV scale gravity. *Phys. Rev. D*, 61:084005, 2000.

[16] E. Churazov, W. Forman, C. Jones, and H. Bohringer. Xmm-newton observations of the perseus cluster I: the temperature and surface brightness structure. *Astrophys. J.*, 590:225–237, 2003.

[17] J. P. Conlon. The QCD axion and moduli stabilisation. *JHEP*, 05:078, 2006.

[18] CTA Coll. Prospects for gamma-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array. *Submitted to JCAP*, xx:xx, 2023.

[19] A. Dominguez et al. Extragalactic Background Light Inferred from AEGIS Galaxy SED-type Fractions. *Mon. Not. Roy. Astron. Soc.*, 410:2556, 2011.

[20] T. P. Li and Y. Q. Ma. Analysis methods for results in gamma-ray astronomy. *Astrophys. J.*, 272:317–324, 1983.

[21] M. Meyer, D. Montanino, and J. Conrad. On detecting oscillations of gamma rays into axion-like particles in turbulent and coherent magnetic fields. *JCAP*, 09:003, 2014.

[22] C. Nigro, T. Hassan, and L. Olivera-Nieto. Evolution of Data Formats in Very-High-Energy Gamma-Ray Astronomy. *Universe*, 7(10):374, 2021.

[23] R. D. Peccei and H. R. Quinn. CP conservation in the presence of pseudoparticles. *Phys. Rev. Lett.*, 38(25):1440–1443, June 1977.

[24] P. Svrcek and E. Witten. Axions In String Theory. *JHEP*, 06:051, 2006.

[25] G. B. Taylor, N. E. Gugliucci, A. C. Fabian, J. S. Sanders, G. Gentile, and S. W. Allen. Magnetic fields in the center of the perseus cluster. *Mon. Not. Roy. Astron. Soc.*, 368:1500–1506, 2006.

[26] N. Turok. Almost Goldstone bosons from extra dimensional gauge theories. *Phys. Rev. Lett.*, 76:1015–1018, 1996.

[27] S. Weinberg. A New Light Boson? *Phys. Rev. Lett.*, 40:223–226, 1978.

[28] F. Wilczek. Problem of Strong P and T Invariance in the Presence of Instantons. *Phys. Rev. Lett.*, 40:279–282, 1978.

[29] E. Witten. Some Properties of O(32) Superstrings. *Phys. Lett. B*, 149:351–356, 1984.

[30] R. Zanin. MARS, the MAGIC analysis and reconstruction software. In *33rd International Cosmic Ray Conference*, page 0773, 2013.

Full Authors List: MAGIC Collaboration

H. Abe[1], S. Abe[1], J. Abhir[2], V. A. Acciari[3], I. Agudo[4], T. Aniello[5], S. Ansoldi[6,46], L. A. Antonelli[5], A. Arbet Engels[7], C. Arcaro[8], M. Artero[9], K. Asano[1], D. Baack[10], A. Babić[11], A. Baquero[12], U. Barres de Almeida[13], J. A. Barrio[12], I. Batković[8], J. Baxter[1], J. Becerra González[3], W. Bednarek[14], E. Bernardini[8], M. Bernardos[4], J. Bernete[15], A. Berti[7], J. Besenrieder[7], C. Bigongiari[5], A. Biland[2], O. Blanch[9], G. Bonnoli[5], Ž. Bošnjak[11], I. Burelli[6], G. Busetto[8], A. Campoy-Ordaz[16], A. Carosi[5], R. Carosi[17], M. Carretero-Castrillo[18], A. J. Castro-Tirado[4], G. Ceribella[7], Y. Chai[7], A. Chilingarian[19], A. Cifuentes[15], S. Cikota[11], E. Colombo[3], J. L. Contreras[12], J. Cortina[15], S. Covino[5], G. D'Amico[20], V. D'Elia[5], P. Da Vela[17,47], F. Dazzi[5], A. De Angelis[8], B. De Lotto[6], A. Del Popolo[21], M. Delfino[9,48], J. Delgado[9,48], C. Delgado Mendez[15], D. Depaoli[22], F. Di Pierro[22], L. Di Venere[23], D. Dominis Prester[24], A. Donini[5], D. Dorner[25], M. Doro[8], D. Elsaesser[10], G. Emery[26], J. Escudero[4], L. Fariña[9], A. Fattorini[10], L. Foffano[5], L. Font[16], S. Fröse[10], S. Fukami[2], Y. Fukazawa[27], R. J. García López[3], M. Garczarczyk[28], S. Gasparyan[29], M. Gaug[16], J. G. Giesbrecht Paiva[13], N. Giglietto[23], F. Giordano[23], P. Gliwny[14], N. Godinović[30], R. Grau[9], D. Green[7], J. G. Green[7], D. Hadasch[1], A. Hahn[7], T. Hassan[15], L. Heckmann[7,49], J. Herrera[3], D. Hrupec[31], M. Hütten[1], R. Imazawa[27], T. Inada[1], R. Iotov[25], K. Ishio[14], I. Jiménez Martínez[15], J. Jormanainen[32], D. Kerszberg[9], G. W. Kluge[20,50], Y. Kobayashi[1], P. M. Kouch[32], H. Kubo[1], J. Kushida[33], M. Láinez Lezáun[12], A. Lamastra[5], D. Lelas[30], F. Leone[5], E. Lindfors[32], L. Linhoff[10], S. Lombardi[5], F. Longo[6,51], R. López-Coto[4], M. López-Moya[12], A. López-Oramas[3], S. Loporchio[23], A. Lorini[34], E. Lyard[26], B. Machado de Oliveira Fraga[13], P. Majumdar[35], M. Makariev[36], G. Maneva[36], N. Mang[10], M. Manganaro[24], S. Mangano[15], K. Mannheim[25], M. Mariotti[8], M. Martínez[9], M. Martínez-Chicharro[15], A. Mas-Aguilar[12], D. Mazin[1,52], S. Menchiari[34], S. Mender[10], S. Mićanović[24], D. Miceli[8], T. Miener[12], J. M. Miranda[34], R. Mirzoyan[7], M. Molero González[3], E. Molina[3], H. A. Mondal[35], A. Moralejo[9], D. Morcuende[12], T. Nakamori[37], C. Nanci[5], L. Nava[5], V. Neustroev[38], L. Nickel[10], M. Nievas Rosillo[3], C. Nigro[9], L. Nikolić[34], K. Nilsson[32], K. Nishijima[33], T. Njoh Ekoume[3], K. Noda[39], S. Nozaki[7], Y. Ohtani[1], T. Oka[40], A. Okumura[41], J. Otero-Santos[3], S. Paiano[5], M. Palatiello[6], D. Paneque[7], R. Paoletti[34], J. M. Paredes[18], L. Pavletić[24], D. Pavlović[24], M. Persic[6,53], M. Pihet[8], G. Pirola[7], F. Podobnik[34], P. G. Prada Moroni[17], E. Prandini[8], G. Principe[6], C. Priyadarshi[9], W. Rhode[10], M. Ribó[18], J. Rico[9], C. Righi[5], N. Sahakyan[29], T. Saito[1], S. Sakurai[1], K. Satalecka[32], F. G. Saturni[5], B. Schleicher[25], K. Schmidt[10], F. Schmuckermaier[7], J. L. Schubert[10], T. Schweizer[7], A. Sciaccaluga[5], J. Sitarek[14], V. Sliusar[26], D. Sobczynska[14], A. Spolon[8], A. Stamerra[5], J. Strišković[31], D. Strom[7], M. Strzys[1], Y. Suda[27], T. Surić[42], S. Suutarinen[32], H. Tajima[41], M. Takahashi[41], R. Takeishi[1], F. Tavecchio[5], P. Temnikov[36], K. Terauchi[40], T. Terzić[24], M. Teshima[7,54], L. Tosti[43], S. Truzzi[34], A. Tutone[5], S. Ubach[16], J. van Scherpenberg[7], M. Vazquez Acosta[3], S. Ventura[34], V. Verguilov[36], I. Viale[8], C. F. Vigorito[22], V. Vitale[44], I. Vovk[1], R. Walter[26], M. Will[7], C. Wunderlich[34], T. Yamamoto[45], [1] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan

[2] ETH Zürich, CH-8093 Zürich, Switzerland

[3] Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain

[4] Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain

[5] National Institute for Astrophysics (INAF), I-00136 Rome, Italy

[6] Università di Udine and INFN Trieste, I-33100 Udine, Italy

[7] Max-Planck-Institut für Physik, D-80805 München, Germany

[8] Università di Padova and INFN, I-35131 Padova, Italy

[9] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain

[10] Technische Universität Dortmund, D-44221 Dortmund, Germany

[11] Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia

[12] IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain

[13] Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil

[14] University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland

[15] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain

[16] Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain

[17] Università di Pisa and INFN Pisa, I-56126 Pisa, Italy

[18] Universitat de Barcelona, ICCUB, IEEC-UB, E-08028 Barcelona, Spain

[19] Armenian MAGIC Group: A. Alikhanyan National Science Laboratory, 0036 Yerevan, Armenia

[20] Department for Physics and Technology, University of Bergen, Norway

[21] INFN MAGIC Group: INFN Sezione di Catania and Dipartimento di Fisica e Astronomia, University of Catania, I-95123 Catania, Italy

[22] INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy

[23] INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, I-70125 Bari, Italy

[24] Croatian MAGIC Group: University of Rijeka, Faculty of Physics, 51000 Rijeka, Croatia

[25] Universität Würzburg, D-97074 Würzburg, Germany

[26] University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland

[27] Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan

[28] Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany

[29] Armenian MAGIC Group: ICRANet-Armenia, 0019 Yerevan, Armenia

[30] Croatian MAGIC Group: University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), 21000 Split, Croatia
[31] Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia
[32] Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, University of Turku, FI-20014 Turku, Finland
[33] Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan
[34] Università di Siena and INFN Pisa, I-53100 Siena, Italy
[35] Saha Institute of Nuclear Physics, A CI of Homi Bhabha National Institute, Kolkata 700064, West Bengal, India
[36] Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
[37] Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan
[38] Finnish MAGIC Group: Space Physics and Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland
[39] Japanese MAGIC Group: Chiba University, ICEHAP, 263-8522 Chiba, Japan
[40] Japanese MAGIC Group: Department of Physics, Kyoto University, 606-8502 Kyoto, Japan
[41] Japanese MAGIC Group: Institute for Space-Earth Environmental Research and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, 464-6801 Nagoya, Japan
[42] Croatian MAGIC Group: Ruđer Bošković Institute, 10000 Zagreb, Croatia
[43] INFN MAGIC Group: INFN Sezione di Perugia, I-06123 Perugia, Italy
[44] INFN MAGIC Group: INFN Roma Tor Vergata, I-00133 Roma, Italy
[45] Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[46] also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy
[47] now at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
[48] also at Port d'Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain
[49] also at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
[50] also at Department of Physics, University of Oslo, Norway
[51] also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[52] Max-Planck-Institut für Physik, D-80805 München, Germany
[53] also at INAF Padova
[54] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan

PoS(ICRC2023)1442