PROCEEDINGS OF SCIENCE

KM3NeT Time calibration with Nanobeacons

Agustín Sánchez Losa,[a,*] Juan Palacios González,[a] Francisco Salesa Greus,[a] Juan Zúñiga Román,[a] Diego Real Máñez[a] and David Calvo Díaz-Aldagalán[a] for the KM3NeT collaboration

[a] *Instituto de Física Corpuscular (CSIC-UV), Parque Científico, C/ Catedrático José Beltrán, 2. Valencia, Spain.*

E-mail: Agustin.Sanchez@ific.uv.es

The KM3NeT Collaboration is building a neutrino telescope in the Mediterranean Sea. The detector is expected to achieve an angular resolution better than 0.1 degrees for energies above 10 TeV. This is critical for attaining one of the key goals of the experiment, i.e. the identification of cosmic neutrino sources. In order to achieve a good angular resolution, the detector requires a relative time calibration of the order of 1 ns.

The Nanobeacon is a cost-effective time calibration device developed by the KM3NeT Collaboration to synchronise *in situ* the detector photomultipliers with a nanosecond relative accuracy. In this contribution we will describe the design and operation of the Nanobeacon. Moreover, we will present the results of data taken in real sea-conditions and we will show how they are used to validate the time calibration parameters measured onshore.

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

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)1062

1. The KM3NeT detectors

The Kilometre Cube Neutrino Telescope (KM3NeT) is a research infrastructure currently under construction in the Mediterranean Sea [1]. It comprises two detectors situated at different locations. The first one, known as ARCA (Astroparticle Research with Cosmics in the Abyss), is being installed off the coast of Capo Passero in Italy at a depth of 3.5 km. The second detector, ORCA (Oscillation Research with Cosmics in the Abyss), is located off the coast of Toulon in France at a depth of 2.5 km. The main scientific goal of ARCA is the detection of high-energy cosmic neutrinos, while ORCA focuses on studying neutrino properties, including neutrino oscillations and neutrino mass hierarchy.

Both detectors share the same hardware, differing only in their layout, which determines the energy range to which they are sensitive. KM3NeT relies on a network of Digital Optical Modules (DOMs) [2], each equipped with 31 photomultiplier tubes (PMTs) measuring 3 inches in diameter [3]. These DOMs are arranged in strings called detector units (DUs), forming a 3D matrix that optimally captures the Čerenkov radiation induced by high-energy neutrinos interacting with the matter surrounding the detector.

Each DOM is controlled by a Central Logic Board (CLB) [4], where all registered data in such DOM is formatted and sent to shore. In particular, when photons are detected by a PMT a "hit" entity is generated. This entity contains the time of detection plus a proxy of the amount of light converted in the PMT photocathode. The latter, called ToT (Time-over-Threshold), is the time the PMT charge has been integrated above a certain detection threshold. The former, is the time when such threshold was exceeded.

In this work, it is discussed how the LED beacon housed in the DOM is used to calibrate one of the corrections that must be applied to the hit time.

2. Time calibration in KM3NeT

Accurate time calibration is a crucial aspect in the operation of neutrino telescopes, playing a fundamental role in event reconstruction, which relies on both, the measurement of the arrival times of the Čerenkov light on the different sensors of the detector and their position estimate at the moment of the light detection. For a detailed description of the determination of the KM3NeT sensor positions see contribution [5].

Čerenkov light propagation through the detector medium introduces unavoidable uncertainties on individual photon detection, partially compensated statistically when, after its propagation, enough light is detected. This contribution is limited by the optical medium, in practice water or ice for neutrino telescopes, and therefore to its scattering and absorption lengths, being better those of water. The remaining uncertainties reside only in the capability to assign a correct time for the photon detection in the PMT photocathode.

Due to various factors, such as signal propagation delays and instrument response time, achieving precise time calibration to millisecond events along a kilometer scale detector poses significant challenges. Absolute time accuracy is limited by the GPS reference used in computers on shore, which in practice implies a few tens of nanosecond accuracy, always below the millisecond, typically enough for astrophysical purposes. On the other hand, the necessary relative time accuracy to

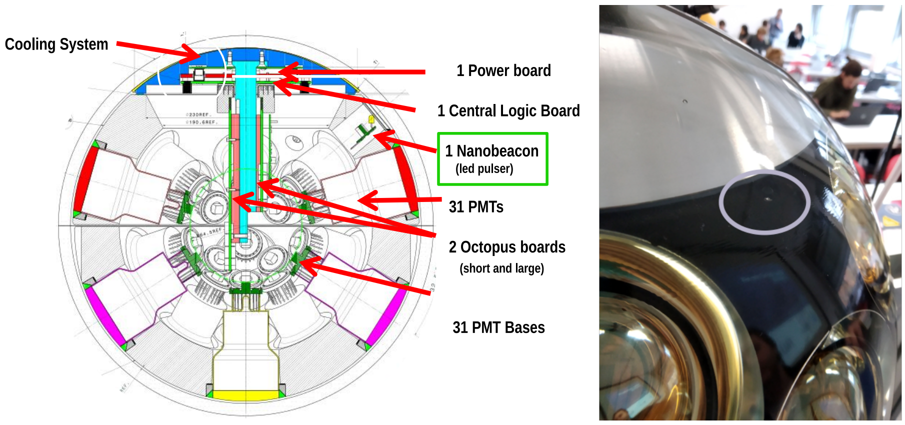

Figure 1: Left: diagram of a KM3NeT DOM, showing the position of the NB LED. Right: A picture of part of the top hemisphere of a DOM with the position of the NB highlighted by a circle. The three closest PMTs used for the flash trigger are partially visible. From [7].

achieve angular resolutions below the degree in a neutrino telescope is at the nanosecond level on the photon detection.

An intrinsic uncertainty contribution comes from the Transit Time Spread of the PMTs, which for KM3NeT is around 2.5 ns [3]. This contribution is compensated statistically in the event reconstruction when the number of detected photons increases.

The time of detection of a hit is assigned by the DOM CLB according to the clock signal propagated along the whole detector infrastructure from the shore computers. This delay is partially estimated during the DU integration in the dark room plus multiple calibrations on parts of the infrastructure. As a result there are three levels of relative time calibration in KM3NeT:

- Intra-DOM: this one reefers to the relative time synchronization of all the PMTs within each DOM. This one can be achieved *in situ* using the K^{40} decays in the sea and looking for the offsets that maximize the coincidences.
- Inter-DOM: that corresponds to the relative timing of the DOMs along the same DU. It is firstly estimated in the dark room using a laser that simultaneously illuminates two reference PMTs in each DOM and can be checked *in situ* using muon tracks and optical beacons, in particular the Nanobeacons.
- Inter-DU: that determines the relative offsets between the different DUs of the detector. It is firstly estimated via multiple calibrations on parts of the infrastructure and during the dark room calibration and can be checked *in situ* using muon tracks (see contribution [6]) and optical beacons, like a laser beacon.

In this work we present the application of the Nanobeacons to the inter-DOM calibration in KM3NeT plus its prospects.

3. Nanobeacon devices

The Nanobeacon (NB) system [7] is an evolution of the LED beacon system [8] mainly used for time calibration purposes in the ANTARES neutrino telescope. The NB has two main components:

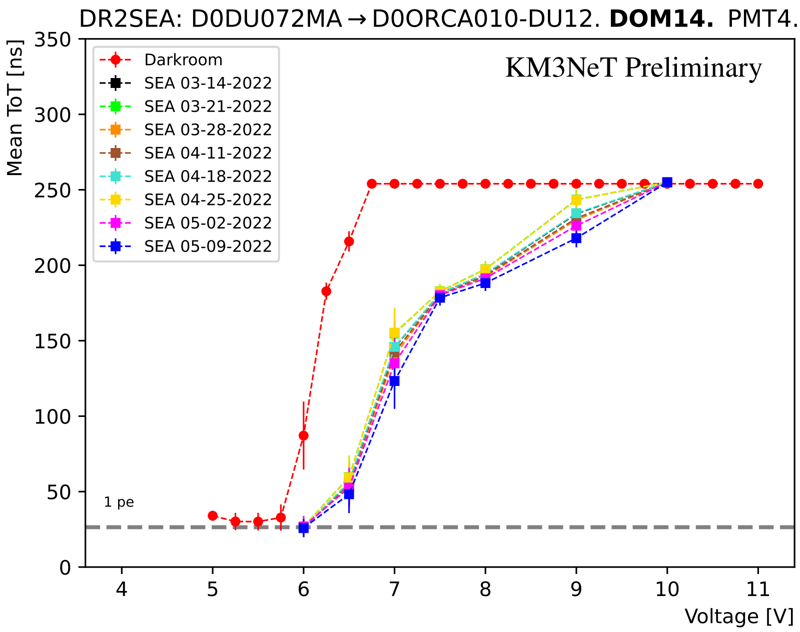

Figure 2: Sigmoid plot for a particular DOM and reference PMT in ORCA.

the pulser and the DC/DC converter. The pulser consists of a LED and an electronics board responsible for generating the trigger signal for the optical pulse. On the other hand, the DC/DC converter is integrated in the power board inside the DOM and delivers the power supply to the NB pulser.

The inherent simplicity of the NB system not only makes it a cost-effective solution but also allows for a smooth integration inside each DOM, providing a high-redundancy calibration of the detector.

In order to mitigate the effects of sedimentation and biofouling on the glass sphere of the DOM, the NB is strategically positioned ~45° off the axis from the top of the DOM, as shown in Figure 1.

The selected LED model was the HLMP-CB1A-XY0DD produced by Broadcom [9]. This model can provide light intensities that are one order of magnitude higher than the intensities provided by the LEDs used in ANTARES.

The NB emits short-duration pulses with a width of approximately 5 ns (FWHM) and a rise time of around 3 ns (from 10% to 90% of full amplitude). The intensity of the pulse is controlled by a configurable voltage that can range between 4.5 and 30 V.

To perform the calibration of the KM3NeT PMTs using the NB system, a reference time is required to accurately establish the moment when the NB flash is emitted. This reference time is obtained by using the three closest PMTs to the NB within the DOM. To prevent data-taking saturation and confirm the NB's emission, a voltage scanning procedure is conducted in a dark room before deploying the DOMs. This scanning helps determine the optimal voltage at which the NB will operate effectively.

The optimal voltage for operating the NB system is expected to vary depending on the medium in which it operates. This is due to the different reflection indices of air (in the dark room) and water (in the sea), resulting in different signals collected by the reference PMTs. Since voltage scanning

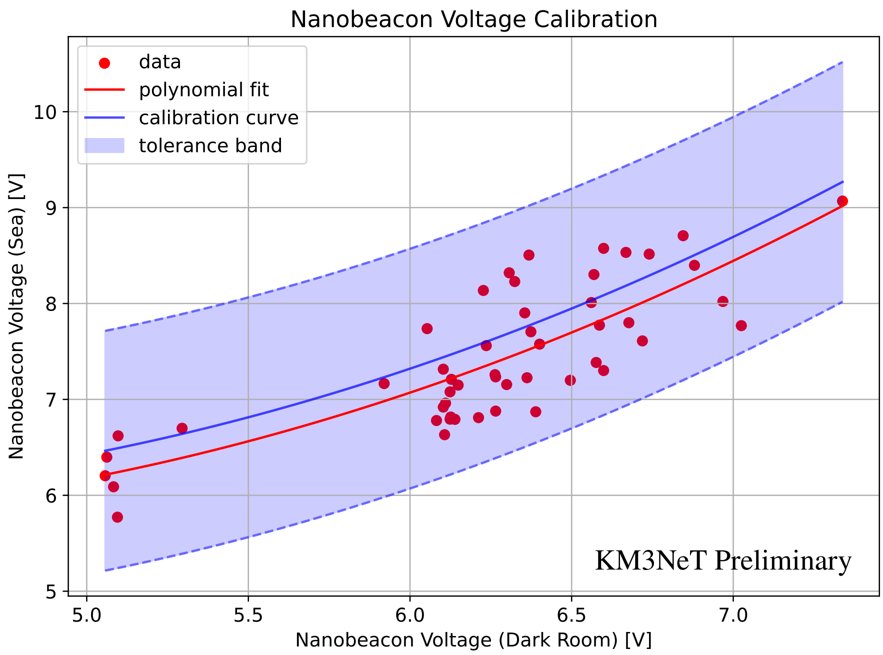

Figure 3: Resulting calibration curve for the NB voltage.

after deploying the DOMs would significantly reduce detector uptime, the scanning process in the sea can only be afforded for a limited number of lines. The characteristic sigmoid-shaped curves resulting from an example of these scanning done in the dark room and in the sea are shown in Fig. 2.

From the sigmoid curve, it is possible to calculate the cumulative distribution and determine the voltage at which the 50th percentile, very stable and robust to determine, is reached. Matching the percentiles for the dark room and sea sigmoids gives the data points shown in Fig. 3. These points exhibit a clear trend which can be fitted to a 2-degree polynomial (red line). To account for fluctuations along the fitted line and minimize cases where the assigned V may not allow proper light emission from the LED, a systematic shift of 0.25 V has been introduced (blue line). This blue line will ultimately be used to determine the appropriate voltage for operating the NB in the sea.

4. Calibration methodology

It is possible to find the relative time offsets between DOMs by illuminating simultaneously various of them with the same NB. This can be done via the detection time of the NB flash measured on each DOM relative to the flash emission corrected by the time it takes the NB light pulse to reach the corresponding DOM. Due to the NB emplacement at the top of the DOM and its PMT distribution, it is intended to be used to illuminate most efficiently and directly the lower PMTs of the DOMs above the flashing NB (see Fig. 4). These DOM pairs, with the most direct light illumination, will be considered for the calibration.

The observed light distribution in the illuminated DOMs follows a Gaussian like distribution, due to the direct light, with a tail due to the scattered light (see Fig. 5). This corrected time difference can be denoted as $\Delta t_0(i, j)$ and under a perfect calibration it will be null. If any of the

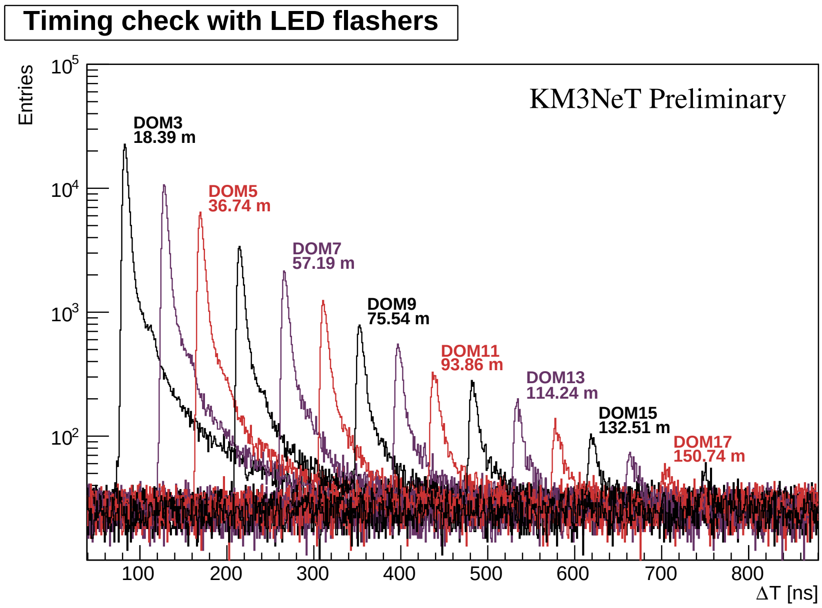

Figure 5: NB illumination of ORCA.0011 line.

implied DOMs has a miscalibrated offset, it will then be $\Delta t_0(i,j) = t_0^j - t_0^i$, where t_0^i would be the miscalibrated time offset of the flashing DOM and t_0^j the one of the illuminated DOM. It is worth to mention that this method will not be sensitive to determine any global absolute offset of the whole DU, that should be determined with an inter-DU calibration, so only DOM relative corrections can be provided.

Being a NB on each DOM, it is possible to have a significant redundancy by considering all the possible pairs of flashing-illuminated DOMs, allowing a robust *in situ* calibration system. For 18 DOMs it is possible to define a system of up to $\frac{1}{2}18(18-1) = 153$ equations, with 17 unknown offsets (one DOM offset can be fixed, e.g. $t_0^1 = 0$, since the method is not sensitive to any DU global offset) which can be summarized as follows:

$$\begin{pmatrix} 1 & 0 & 0 & \cdots & 0 & 0 \\ -1 & 1 & 0 & \cdots & 0 & 0 \\ -1 & 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 \end{pmatrix} \begin{pmatrix} t_0^1 \\ t_0^2 \\ t_0^3 \\ \vdots \\ t_0^{18} \end{pmatrix} = \begin{pmatrix} 0 \\ \Delta t_0(1,2) \\ \Delta t_0(1,3) \\ \vdots \\ \Delta t_0(17,18) \end{pmatrix} \tag{1}$$

or more compactly:

$$M_{mn} \cdot (T_0)_n = (\Delta T_0)_m \tag{2}$$

with $m = 1, ..., 154$ and $n = 1, ..., 18$.

Each available $\Delta t_0(i,j)$ pair can be estimated from a Gaussian fit to the time difference distribution. This fit has an associated error $\sigma_\mu^{i,j}$ that can be introduced in the least squares solutions by means of a weighting covariance matrix W:

$$W_{mm} = diag\left(\frac{1}{x^2}, \frac{1}{(\sigma_\mu^{1,2})^2}, \frac{1}{(\sigma_\mu^{1,3})^2}, \cdots, \frac{1}{(\sigma_\mu^{17,18})^2}\right) \tag{3}$$

This will be helpful since sometimes the $\Delta t_0(i, j)$ fits can be not optimal nor very reliable, weighting them out when solving the system in eq. 2 via:

$$W_{mm} \cdot M_{mn} \cdot (T_0)_n = W_{mm} \cdot (\Delta T_0)_m \tag{4}$$

leading to the system solution:

$$(T_0)_n = \left(M^T_{nm} \cdot W_{mm} \cdot M_{mn}\right)^{-1} \cdot M^T_{nm} \cdot W_{mm} \cdot (\Delta T_0)_m \tag{5}$$

A covariance matrix $\mathbb{V}$ for the time offsets can also be defined:

$$\mathbb{V} = \left(M^T_{nm} \cdot W_{mm} \cdot M_{mn}\right)^{-1} \tag{6}$$

allowing to evaluate the goodness of the found offsets.

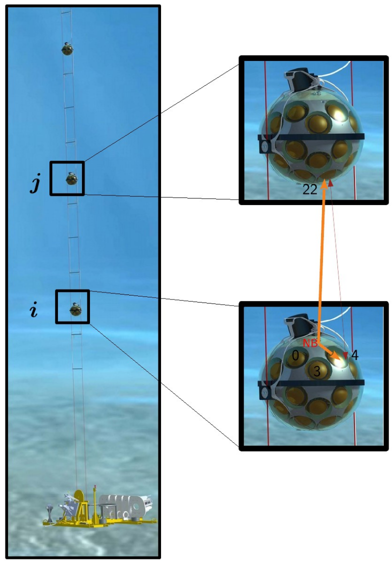

Figure 4: Concept of NB time calibration. DOM i NB flash is detected by the closest PMTs and observed mostly by those at the bottom of DOM j.

5. Results

This calibration method has been applied to *in situ* NB data (see an example in Fig. 6) assuming a preliminary fixed geometry of the detector and mostly confirming the goodness of the dark room inter-DOM calibration. Further checks with a revised geometry are on-going. It will be used to determine the inter-DOM offset of the few DOMs that, due to technical issues, were not possible to calibrate during the dark room phase. For the future it is planned to design a sustainable NB data taking to scale reasonably up to the whole detector including the optimally tuned NB voltages described in this work.

6. Acknowledgments

The authors acknowledge the financial support from Ministerio de Ciencia, Innovación, Investigación y Universidades (MCIU): reference PGC2018-096663-B-C41; Ministerio de Ciencia e Innovación (MCI): reference PID2021-124591NB-C41; and Generalitat Valenciana: references CIDEGENT/2018/034 and CIDEGENT/2020/049. Also, this research was supported by an FPU grant (Formación de Profesorado Universitario) from the Spanish Ministry of Universities (MIU) to Juan Palacios González (reference FPU20/03176).

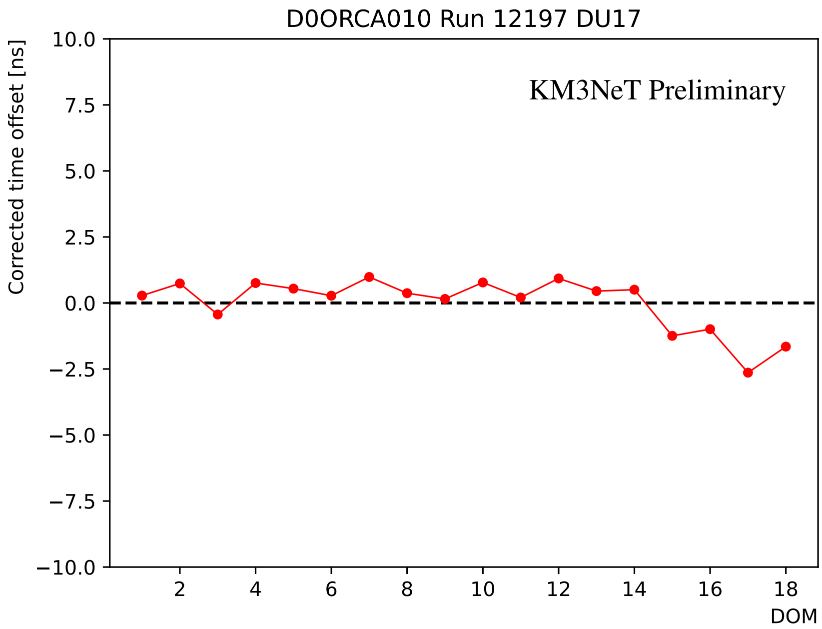

Figure 6: NB time calibration.

References

[1] S. Adrian-Martinez *et al.* [KM3NeT], J. Phys. G **43** (2016) no.8, 084001 doi:10.1088/0954-3899/43/8/084001 [arXiv:1601.07459 [astro-ph.IM]].

[2] S. Aiello *et al.* [KM3NeT], JINST **17** (2022) no.07, P07038 doi:10.1088/1748-0221/17/07/P07038 [arXiv:2203.10048 [astro-ph.IM]].

[3] S. Aiello *et al.* [KM3NeT], JINST **13** (2018) no.05, P05035 doi:10.1088/1748-0221/13/05/P05035

[4] S. Aiello *et al.* [KM3NeT], J. Astron. Telesc. Instrum. Syst. **5** (2019) no.4, 046001 doi:10.1117/1.JATIS.5.4.046001 [arXiv:1907.06453 [astro-ph.IM]].

[5] Clara Gatius Oliver [KM3NeT], PoS(ICRC2023)1033 (these proceedings).

[6] Louis Bailly-Salins [KM3NeT], PoS(ICRC2023)218 (these proceedings).

[7] S. Aiello *et al.* [KM3NeT], Nucl. Instrum. Meth. A **1040** (2022), 167132 doi:10.1016/j.nima.2022.167132 [arXiv:2111.00223 [astro-ph.IM]].

[8] M. Ageron *et al.* [ANTARES], Nucl. Instrum. Meth. A **578** (2007), 498-509 doi:10.1016/j.nima.2007.05.325 [arXiv:astro-ph/0703355 [astro-ph]].

[9] Broadcom Inc. *HLMP-CB1A-XY0DD LED model*. Accessed: July 4, 2023. Available online: https://www.broadcom.com/products/leds-and-displays/high-brightness/round-through-hole-lamps/hlmp-cb1a-xy0dd.

Full Authors List: The KM3NeT Collaboration

S. Aiello[a], A. Albert[b,bd], S. Alves Garre[c], Z. Aly[d], A. Ambrosone[f,e], F. Ameli[g], M. Andre[h], E. Androutsou[i], M. Anguita[j], L. Aphecetche[k], M. Ardid[l], S. Ardid[l], H. Atmani[m], J. Aublin[n], L. Bailly-Salins[o], Z. Bardačová[q,p], B. Baret[n], A. Bariego-Quintana[c], S. Basegmez du Pree[r], Y. Becherini[n], M. Bendahman[m,n], F. Benfenati[t,s], M. Benhassi[u,e], D. M. Benoit[v], E. Berbee[r], V. Bertin[d], S. Biagi[w], M. Boettcher[x], D. Bonanno[w], J. Boumaaza[m], M. Bouta[y], M. Bouwhuis[r], C. Bozza[z,e], R. M. Bozza[f,e], H.Brânzaş[aa], F. Bretaudeau[k], R. Bruijn[ab,r], J. Brunner[d], R. Bruno[a], E. Buis[ac,r], R. Buompane[u,e], J. Busto[d], B. Caiffi[ad], D. Calvo[c], S. Campion[g,ae], A. Capone[g,ae], F. Carenini[t,s], V. Carretero[c], T. Cartraud[n], P. Castaldi[af,s], V. Cecchini[c], S. Celli[g,ae], L. Cerisy[d], M. Chabab[ag], M. Chadolias[ah], A. Chen[ai], S. Cherubini[aj,w], T. Chiarusi[s], M. Circella[ak], R. Cocimano[w], J. A. B. Coelho[n], A. Coleiro[n], R. Coniglione[w] P. Coyle[d], A. Creusot[n], A. Cruz[al], G. Cuttone[w], R. Dallier[k], Y. Darras[ah], A. De Benedittis[e], B. De Martino[d], V. Decoene[k], R. Del Burgo[e], U. M. Di Cerbo[e], L. S. Di Mauro[w], I. Di Palma[g,ae], A. F. Díaz[j], C. Diaz[j], D. Diego-Tortosa[w], C. Distefano[w], A. Domi[ah], C. Donzaud[n], D. Dornic[d], M. Dörr[am], E. Drakopoulou[i], D. Drouhin[b,bd], R. Dvornický[q], T. Eberl[ah], E. Eckerová[q,p], A. Eddymaoui[m], T. van Eeden[r], M. Eff[n], D. van Eijk[r], I. El Bojaddaini[y], S. El Hedri[n], A. Enzenhöfer[d], G. Ferrara[w], M. D. Filipović[an], F. Filippini[t,s], D. Franciotti[w], L. A. Fusco[z,e], J. Gabriel[ao], S. Gagliardini[g], T. Gal[ah], J. García Méndez[l], A. Garcia Soto[c], C. Gatius Oliver[r], N. Geißelbrecht[ah], H. Ghaddari[y], L. Gialanella[e,u], B. K. Gibson[v], E. Giorgio[w], I. Goos[n], D. Goupilliere[o], S. R. Gozzini[c], R. Gracia[ah], K. Graf[ah], C. Guidi[ap,ad], B. Guillon[o], M. Gutiérrez[aq], H. van Haren[ar], A. Heijboer[r], A. Hekalo[am], L. Hennig[ah], J. J. Hernández-Rey[c], F. Huang[d], W. Idrissi Ibnsalih[e], G. Illuminati[s], C. W. James[al], M. de Jong[as,r], P. de Jong[ab,r], B. J. Jung[r], P. Kalaczyński[at,be], O. Kalekin[ah], U. F. Katz[ah], N. R. Khan Chowdhury[c], A. Khatun[q], G. Kistauri[av,au], C. Kopper[ah], A. Kouchner[aw,n], V. Kulikovskiy[ad], R. Kvatadze[av], M. Labalme[o], R. Lahmann[ah], G. Larosa[w], C. Lastoria[d], A. Lazo[c], S. Le Stum[d], G. Lehaut[o], E. Leonora[a], N. Lessing[c], G. Levi[t,s], M. Lindsey Clark[n], F. Longhitano[a], J. Majumdar[r], L. Malerba[ad], F. Mamedov[p], J. Mańczak[c], A. Manfreda[e], M. Marconi[ap,ad], A. Margiotta[t,s], A. Marinelli[e,f], C. Markou[i], L. Martin[k], J. A. Martínez-Mora[l], F. Marzaioli[u,e], M. Mastrodicasa[ae,g], S. Mastroianni[e], S. Miccichè[w], G. Miele[f,e], P. Migliozzi[e], E. Migneco[w], S. Minutoli[ad], M. L. Mitsou[e], C. M. Mollo[e], L. Morales-Gallegos[u,e], C. Morley-Wong[al], A. Moussa[y], I. Mozun Mateo[ay,ax], R. Muller[r], M. R. Musone[e,u], M. Musumeci[w], L. Nauta[r], S. Navas[aq], A. Nayerhoda[ak], C. A. Nicolau[g], B. Nkosi[ai], B. Ó Fearraigh[ab,r], V. Oliviero[f,e], A. Orlando[w], E. Oukacha[n], D. Paesani[w], J. Palacios González[c], G. Papalashvili[au], V. Parisi[ap,ad], E.J. Pastor Gomez[c], A. M. Păun[aa], G. E. Păvălaş[aa], S. Peña Martínez[n], M. Perrin-Terrin[d], J. Perronnel[o], V. Pestel[ay], R. Pestes[n], P. Piattelli[w], C. Poirè[z,e], V. Popa[aa], T. Pradier[b], S. Pulvirenti[w], G. Quéméner[o], C. Quiroz[l], U. Rahaman[c], N. Randazzo[a], R. Randriatoamanana[k], S. Razzaque[az], I. C. Rea[e], D. Real[c], S. Reck[ah], G. Riccobene[w], J. Robinson[x], A. Romanov[ap,ad], A. Šaina[c], F. Salesa Greus[c], D. F. E. Samtleben[as,r], A. Sánchez Losa[c,ak], S. Sanfilippo[w], M. Sanguineti[ap,ad], C. Santonastaso[ba,e], D. Santonocito[w], P. Sapienza[w], J. Schnabel[ah], J. Schumann[ah], H. M. Schutte[x], J. Seneca[r], N. Sennan[y], B. Setter[ah], I. Sgura[ak], R. Shanidze[au], Y. Shitov[p], F. Šimkovic[q], A. Simonelli[e], A. Sinopoulou[a], M.V. Smirnov[ah], B. Spisso[e], M. Spurio[t,s], D. Stavropoulos[i], I. Štekl[p], M. Taiuti[ap,ad], Y. Tayalati[m], H. Tedjditi[ad], H. Thiersen[x], I. Tosta e Melo[a,aj], B. Trocmé[n], V. Tsourapis[i], E. Tzamariudaki[i], A. Vacheret[o], V. Valsecchi[w], V. Van Elewyck[aw,n], G. Vannoye[d], G. Vasileiadis[bb], F. Vazquez de Sola[r], C. Verilhac[n], A. Veutro[g,ae], S. Viola[w], D. Vivolo[u,e], J. Wilms[bc], E. de Wolf[ab,r], H. Yepes-Ramirez[l], G. Zarpapis[i], S. Zavatarelli[ad], A. Zegarelli[g,ae], D. Zito[w], J. D. Zornoza[c], J. Zúñiga[c], and N. Zywucka[x].

[a]INFN, Sezione di Catania, Via Santa Sofia 64, Catania, 95123 Italy
[b]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[c]IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València), c/Catedrático José Beltrán, 2, 46980 Paterna, Valencia, Spain
[d]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[e]INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[f]Università di Napoli "Federico II", Dip. Scienze Fisiche "E. Pancini", Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[g]INFN, Sezione di Roma, Piazzale Aldo Moro 2, Roma, 00185 Italy
[h]Universitat Politècnica de Catalunya, Laboratori d'Aplicacions Bioacústiques, Centre Tecnològic de Vilanova i la Geltrú, Avda. Rambla Exposició, s/n, Vilanova i la Geltrú, 08800 Spain
[i]NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attikis, Athens, 15310 Greece
[j]University of Granada, Dept. of Computer Architecture and Technology/CITIC, 18071 Granada, Spain
[k]Subatech, IMT Atlantique, IN2P3-CNRS, Université de Nantes, 4 rue Alfred Kastler - La Chantrerie, Nantes, BP 20722 44307 France
[l]Universitat Politècnica de València, Instituto de Investigación para la Gestión Integrada de las Zonas Costeras, C/ Paranimf, 1, Gandia, 46730 Spain
[m]University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[n]Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[o]LPC CAEN, Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, 6 boulevard Maréchal Juin, Caen, 14050 France
[p]Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, Prague, 110 00 Czech Republic
[q]Comenius University in Bratislava, Department of Nuclear Physics and Biophysics, Mlynska dolina F1, Bratislava, 842 48 Slovak Republic
[r]Nikhef, National Institute for Subatomic Physics, PO Box 41882, Amsterdam, 1009 DB Netherlands
[s]INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[t]Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[u]Università degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Matematica e Fisica, viale Lincoln 5, Caserta, 81100 Italy
[v]E. A. Milne Centre for Astrophysics, University of Hull, Hull, HU6 7RX, United Kingdom

[w]INFN, Laboratori Nazionali del Sud, Via S. Sofia 62, Catania, 95123 Italy
[x]North-West University, Centre for Space Research, Private Bag X6001, Potchefstroom, 2520 South Africa
[y]University Mohammed I, Faculty of Sciences, BV Mohammed VI, B.P. 717, R.P. 60000 Oujda, Morocco
[z]Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[aa]ISS, Atomistilor 409, Măgurele, RO-077125 Romania
[ab]University of Amsterdam, Institute of Physics/IHEF, PO Box 94216, Amsterdam, 1090 GE Netherlands
[ac]TNO, Technical Sciences, PO Box 155, Delft, 2600 AD Netherlands
[ad]INFN, Sezione di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[ae]Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy
[af]Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "Guglielmo Marconi", Via dell'Università 50, Cesena, 47521 Italia
[ag]Cadi Ayyad University, Physics Department, Faculty of Science Semlalia, Av. My Abdellah, P.O.B. 2390, Marrakech, 40000 Morocco
[ah]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Straße 2, 91058 Erlangen, Germany
[ai]University of the Witwatersrand, School of Physics, Private Bag 3, Johannesburg, Wits 2050 South Africa
[aj]Università di Catania, Dipartimento di Fisica e Astronomia "Ettore Majorana", Via Santa Sofia 64, Catania, 95123 Italy
[ak]INFN, Sezione di Bari, via Orabona, 4, Bari, 70125 Italy
[al]International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia
[am]University Würzburg, Emil-Fischer-Straße 31, Würzburg, 97074 Germany
[an]Western Sydney University, School of Computing, Engineering and Mathematics, Locked Bag 1797, Penrith, NSW 2751 Australia
[ao]IN2P3, LPC, Campus des Cézeaux 24, avenue des Landais BP 80026, Aubière Cedex, 63171 France
[ap]Università di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[aq]University of Granada, Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., 18071 Granada, Spain
[ar]NIOZ (Royal Netherlands Institute for Sea Research), PO Box 59, Den Burg, Texel, 1790 AB, the Netherlands
[as]Leiden University, Leiden Institute of Physics, PO Box 9504, Leiden, 2300 RA Netherlands
[at]National Centre for Nuclear Research, 02-093 Warsaw, Poland
[au]Tbilisi State University, Department of Physics, 3, Chavchavadze Ave., Tbilisi, 0179 Georgia
[av]The University of Georgia, Institute of Physics, Kostava str. 77, Tbilisi, 0171 Georgia
[aw]Institut Universitaire de France, 1 rue Descartes, Paris, 75005 France
[ax]IN2P3, 3, Rue Michel-Ange, Paris 16, 75794 France
[ay]LPC, Campus des Cézeaux 24, avenue des Landais BP 80026, Aubière Cedex, 63171 France
[az]University of Johannesburg, Department Physics, PO Box 524, Auckland Park, 2006 South Africa
[ba]Università degli Studi della Campania "Luigi Vanvitelli", CAPACITY, Laboratorio CIRCE - Dip. Di Matematica e Fisica - Viale Carlo III di Borbone 153, San Nicola La Strada, 81020 Italy
[bb]Laboratoire Univers et Particules de Montpellier, Place Eugène Bataillon - CC 72, Montpellier Cédex 05, 34095 France
[bc]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Remeis Sternwarte, Sternwartstraße 7, 96049 Bamberg, Germany
[bd]Université de Haute Alsace, rue des Frères Lumière, 68093 Mulhouse Cedex, France
[be]AstroCeNT, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rektorska 4, Warsaw, 00-614 Poland

Acknowledgements

The authors acknowledge the financial support of the funding agencies: Agence Nationale de la Recherche (contract ANR-15-CE31-0020), Centre National de la Recherche Scientifique (CNRS), Commission Européenne (FEDER fund and Marie Curie Program), LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001), Paris Île-de-France Region, France; Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-22-13708), Georgia; The General Secretariat of Research and Innovation (GSRI), Greece Istituto Nazionale di Fisica Nucleare (INFN), Ministero dell'Università e della Ricerca (MIUR), PRIN 2017 program (Grant NAT-NET 2017W4HA7S) Italy; Ministry of Higher Education, Scientific Research and Innovation, Morocco, and the Arab Fund for Economic and Social Development, Kuwait; Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; The National Science Centre, Poland (2021/41/N/ST2/01177); The grant "AstroCeNT: Particle Astrophysics Science and Technology Centre", carried out within the International Research Agendas programme of the Foundation for Polish Science financed by the European Union under the European Regional Development Fund; National Authority for Scientific Research (ANCS), Romania; Grants PID2021-124591NB-C41, -C42, -C43 funded by MCIN/AEI/ 10.13039/501100011033 and, as appropriate, by "ERDF A way of making Europe", by the "European Union" or by the "European Union NextGenerationEU/PRTR", Programa de Planes Complementarios I+D+I (refs. ASFAE/2022/023, ASFAE/2022/014), Programa Prometeo (PROMETEO/2020/019) and GenT (refs. CIDEGENT/2018/034, /2019/043, /2020/049. /2021/23) of the Generalitat Valenciana, Junta de Andalucía (ref. SOMM17/6104/UGR, P18-FR-5057), EU: MSC program (ref. 101025085), Programa María Zambrano (Spanish Ministry of Universities, funded by the European Union, NextGenerationEU), Spain; The European Union's Horizon 2020 Research and Innovation Programme (ChETEC-INFRA - Project no. 101008324).

PoS(ICRC2023)1062