PROCEEDINGS OF SCIENCE

Refined neutrino follow-up analysis of GRB 221009A with KM3NeT ARCA and ORCA detectors

J. Palacios González,[a,*] S. Le Stum,[b] D. Dornic,[b] F. Filippini,[c] G. Illuminati,[c] F. Salesa Greus,[a] A. Sánchez Losa,[a] G. Vannoye[b] and A. Zegarelli[d] for the KM3NeT collaboration

[a] *Instituto de Física Corpuscular (CSIC-UV). Valencia, Spain.*
[b] *Aix Marseille University, CNRS/IN2P3, CPPM, Marseille, France.*
[c] *Dipartimento di Fisica e Astronomia dell' Università, Bologna, Italy, and INFN, Sezione di Bologna, Bologna, Italy.*
[d] *Dipartamento di Fisica, Universita' Sapienza. Roma, Italy, and INFN, Sezione di Roma, Roma, Italy.*

E-mail: Juan.Palacios@ific.uv.es, lestum@cppm.in2p3.fr

On October 9th 2022, the Swift-BAT telescope detected a spectacular transient event, soon classified as a Gamma-Ray Burst (GRB), based on the Fermi-GBM observation performed one hour earlier. Photons up to TeV energies were observed from such GRB by LHAASO, corresponding to the highest energy ever detected from a GRB. Just after this detection, a large number of observatories detected and characterized the multi-wavelength and multi-messenger emissions of this GRB, in one of the largest worldwide follow-up campaigns ever.

The KM3NeT neutrino telescope was one of the experiments that participated in the follow-up effort. KM3NeT is currently being built in the Mediterranean Sea and is composed of two detectors: ORCA, optimized for the detection of signals induced by neutrinos in the GeV-TeV range, and ARCA, mainly focused in neutrinos at the TeV-PeV range. MeV neutrinos can also be detected by looking for rate coincidences of Photo-Multipliers Tubes signals in both detectors. A first fast analysis was performed using data from the online reconstruction chain. In this contribution, we present a refined follow-up analysis, where new offline features are added together with improved calibration and optimized event selection.

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

*Speaker

1. GRB 221009A

On 2022 October 9, at 13:16:59.0 UT (T_0 from now on) the GBM instrument onboard the Fermi satellite triggered an extraordinarily bright transient phenomenon [1]. Shortly later, at 14:10:17 UT, the Swift-BAT telescope also detected a transient event consistent with the location of Fermi-GBM (but with better accuracy) and with candidate counterparts by Swift-XRT and Swift-UVOT [2]. The event was located at RA=288.263° and DEC= +19.803° (J2000) with an uncertainty of 3 arc mins. The transient was quickly identified as a long Gamma-Ray Burst (GRB), probably as a consequence of the collapse of a supermassive star.

GRB 221009A is one of the brightest gamma-ray bursts ever detected. Notably, the LHAASO gamma-ray observatory reported the observation of this event at unprecedented TeV energies [3]. Fermi-LAT also detected photons with energies up to $\sim$ 99 GeV, being the highest energies ever detected by such instrument [4].

This GRB is a relatively nearby event, with a redshift of $z = 0.151$ and an isotropic energy of at least $2 \cdot 10^{54}$ erg based on the gamma-ray fluence measured by Fermi-GBM [5]. The proximity, together with the fact that the jet emission is thought to be very collimated [6], could explain the extraordinary brightness of this event.

GRB 221009A has been proposed to be a collapsar, i.e. a very energetic supernova that results from an extreme core-collapse scenario [7]. However, there has not been observed clear evidence for a supernova signal [8]. Results from this long GRB have been reported by various multi-wavelength facilities such as MAXI/GSC [9], INTEGRAL SPI/ACS [10] or HAWC [11], among others. Close to fifty entries were published in the Gamma-ray Coordinate Network (GCN) [12] during the three days after the event, which proves the relevance of the event for the astrophysical community and motivates multi-messenger campaigns.

The peculiar characteristics of this GRB made it very interesting also for neutrino astronomy studies. Indeed, there are several models that predict the emission of TeV-PeV neutrinos from GRBs as a result of hadronic interactions of protons with high-density matter or radiation field photons [13]. The IceCube Neutrino Observatory reported the results of a fast follow-up one day after the event [14]. The analysis was based on two track-like muon neutrino searches:

- Using a time window $[T_0 - 1\text{ h}, T_0 + 2\text{ h}]$: no track-like events were found in coincidence. The upper limit of the time-integrated muon-neutrino flux was set at $E^2 dN/dE = 3.9 \cdot 10^{-2}$ GeV cm^{-2} at 90% CL (assuming an E^{-2} power law).

- During a time window of $T_0 \pm 1$ day: a p-value of 1.0 was reported, consistent with background expectations. In this case, the time-integrated muon-neutrino flux upper limit was set at $E^2 dN/dE = 4.1 \cdot 10^{-2}$ GeV cm^{-2} at 90% CL (assuming an E^{-2} power law).

A refined search was published months later by the IceCube Collaboration, including restrictive upper limits in the neutrino emission from GRB 22100A in a broad energy range [15].

The KM3NeT Collaboration also reported results for a quick follow-up search three days after the event [16]. Indeed, the Online KM3NeT framework [17, 18] for multi-messenger studies was in the commissioning period at that time. Three different real-time analyses were performed:

- A low energy analysis in the MeV range, based on the search for the maximum number of 10 ns coincidences between Photo-Multipliers Tubes (PMTs) in single modules during 500 ms, computed every 100 ms. A post-trial p-value of 0.9 was reported, compatible with background expectations.

- Two high-energy searches (one for KM3NeT/ORCA and one for KM3NeT/ARCA) based on binned techniques [18]. In the case of ARCA (ORCA) a search cone with a radius of 4° (2°) centered around the GRB position and the time window [T0−50 s, T0+5000 s] were used, with zero events observed and ~ 0.1 events expected from the atmospheric background.

The present work includes a refined search for neutrino emission from GRB 221009A using KM3NeT data, including new features such as improved calibrations and dedicated Monte Carlo (MC) simulations. Section 2 includes a detailed description of the KM3NeT detectors. Section 3 describes the method used to perform the follow-up analysis. The results and the conclusions are provided in Sections 4 and 5, respectively.

2. The KM3NeT detectors

KM3NeT [19] (Cubic Kilometre Neutrino Telescope) is an international collaborative project currently deploying two deep-sea detectors in the Mediterranean Sea. These detectors consist of three-dimensional arrays of PMTs, able to detect the Cherenkov light emitted by particles resulting from neutrino interactions in seawater. The construction comprises two separate arrays: ORCA (Oscillation Research with Cosmics in the Abyss) and ARCA (Astroparticle Research with Cosmic in the Abyss).

On one hand, ORCA, located 40 km from Toulon at a depth of 2.5 km, is designed to study atmospheric neutrino oscillations and the neutrino mass hierarchy. On the other hand, ARCA, located 100 km from Portopalo di Capo Passero, Sicily, at a depth of 3.5 km, is optimized for studying high-energy neutrinos originating from astrophysical sources. The complementarity of the two detectors allows to study neutrinos from the MeV range up to PeV energies.

The main components of the KM3NeT detectors are the Digital Optical Modules (DOMs) [20], pressure-resistant glass spheres, each housing 31 PMTs. This multi-PMT approach, as opposed to using a single large PMT in each module, offers advantages such as the ability to identify physical signals through coincident hits on the same DOM. Each vertical string of 18 DOMs is called a Detection Unit (DU), and a grouping of 115 DUs forms a building block.

ORCA has a higher DOM density that enables it to study neutrinos in the GeV energy range. In contrast, ARCA has a lower density of DOMs, allowing it to cover a broader energy range, spanning from the sub-TeV range up to a few PeVs. This complementary between the two detectors motivates studies across a wide energy spectrum. Additionally, the high-duty cycle (> 95%) and the good angular resolution of the detectors (below one degree for $E > 10$ TeV) make them excellently suited instruments to perform multi-messenger studies such as the present work.

During October 2022, when GRB 221009A took place, ARCA had 21 DUs in operation, while ORCA counted 10 DUs. These partial configurations were taking good-quality data, monitoring the sky searching for neutrino signals.

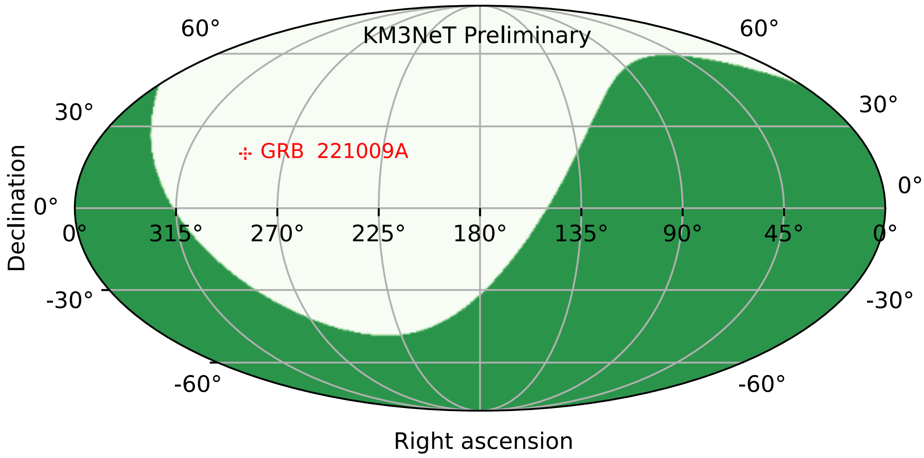

Figure 1: Skymap with the position of GRB 221009A in equatorial coordinates. The green shadowed region indicates the instantaneous visibility for upgoing events of KM3NeT/ARCA at the moment of the event (similar to the one of KM3NeT/ORCA).

3. Search method

As mentioned in Section 1, the data used in this analysis are at a refined calibration level with respect to the first, fast analyses performed earlier. An acoustic dynamical correction has been implemented to estimate the positions of the DOMs after the lines displacement due to currents in the seabed [21]. Additionally, a dedicated MC has been produced to compute the expected signal and set upper limits in the fluence emission.

As GRB position, the one given by Swift-BAT has been considered [2] (due to its better angular resolution) using as T_0 the trigger time by Fermi-GBM [1]. Three different time windows have been investigated using both ARCA and ORCA independently:

- One short-duration search in the range $[T_0 - 50\text{ s}, T_0 + 5000\text{ s}]$, as the online follow-up, with a downgoing track event selection (i.e. events reconstructed as not crossing the Earth).
- Two long-duration searches in the range $T_0 \pm 1$ day: one using an upgoing track event selection (i.e. events reconstructed as crossing the Earth) and another with a downgoing one.

The format of these searches is motivated by the fact that GRB 221009A was in the downgoing sky of the KM3NeT detectors at the time of the event, as shown in Figure 1. The analyses have been conducted by selecting only the corresponding upgoing or downgoing events during the period of the time windows considered. Indeed, for 45.2% of the time during one day, the location in the sky of GRB 221009A was found to be in the upgoing sky of the KM3NeT detectors.

The search method is based on a binned ON/OFF technique [22]. The ON region is defined as the area of the sky where the signal is expected to dominate over the atmospheric background, while the OFF region is defined as a region comparable to the ON region where only background is expected. We use as ON region a circular cone centered in the GRB position, which represents the Region of Interest (RoI) of the analysis. The OFF region is a declination/elevation band (for time windows above/below the day range) that is re-scaled in solid angle and time to the ON region size.

The event selection is based on the reconstruction variables of track-like events, i.e. events with a straight-line pattern that are originated in charged-current interactions from muon-flavour neutrinos and some tau-flavour. These events represent the ones with the best angular resolution. Cascade-like events, i.e. spherical-pattern events that emerge from electron-neutrino and some tau-flavour charged-current interactions, and neutral-current neutrino interactions, are not considered in this analysis.

The selection has been optimized in order to achieve a background level where one single event in the ON region provides a 3σ excess with respect to the expected background. Using a 2-sided convention, this corresponds to an expected background $\leq 2.7 \cdot 10^{-3}$ events. From all the event selections that fulfill this condition, we select the one that provides the largest expected signal, which has been computed from MC simulations assuming a neutrino flux $\phi \propto E^{-2}$. Systematic effects have been taken into account in these expectations computed from simulations, such as the uncertainty in the reconstruction direction of the data events.

For KM3NeT/ORCA, a data livetime of ~41 days has been used to estimate the expected background in the OFF region, re-scaled in time to the ON region time window. Consideration has been given to ensure stable data-taking conditions during the period studied. The event selection optimization is done on a machine learning classification score [23] that aims to reduce the large background of atmospheric muon events. After some minimal quality cuts, the 3σ-1event optimization has been performed to determine the optimum values for the classification score and the RoI radius.

For KM3NeT/ARCA, a similar stability study has been conducted using a sample with ~70 days of livetime. This analysis applies straightforward selections on the reconstruction variables of the track-like events. In concrete, the optimization focuses on the quality of the event reconstruction, the estimated angular uncertainty of the event, the number of hits used in the reconstruction, and the estimated length of the track event in meters. The latter variable, which is useful to reject atmospheric muons misreconstructed as upgoing, is substituted in the downgoing analyses by a cut in the energy estimator in order to address the high atmospheric muon contamination in this part of the sky.

4. Results

After the optimization procedure described in Section3, the KM3NeT data was unblinded. No candidate neutrino event has been found in any of the searches performed. The expected signal events (from MC simulations) together with the expected background events (from data in the OFF region) are provided in Table 1.

Given a null result in the correlation analyses, upper limits (UL) in the neutrino emission from GRB 221009A were determined. The 90% CL UL in the flux normalization factor is defined as

$$\Phi_0^{\mathrm{UL}}\ (90\%\ \mathrm{CL}) \equiv \frac{\mu_{90}^{FC}(n_b)}{Acc}, \tag{1}$$

where $\mu_{90}^{FC}(n_b)$ denotes the 90% CL UL in the number of events by Feldman-Cousins [24]. Acc in eq. 1 stands for the detector acceptance, a quantity defined as the proportionality constant that relates the number of expected signal events with a given flux normalization.

ANALYSIS	RoI radius	Expected signal events	Expected background events	Events in ON region
ARCA upgoing $T_0 \pm 1$ day	1.7°	$4.7 \cdot 10^{-3}$	$(2.7 \pm 0.2) \cdot 10^{-3}$	0
ARCA downgoing $T_0 \pm 1$ day	1.0°	$1.2 \cdot 10^{-3}$	$(2.6 \pm 0.1) \cdot 10^{-3}$	0
ARCA downgoing $T_0[-50\text{s}, +5000\text{s}]$	1.2°	$4.4 \cdot 10^{-5}$	$(2.66 \pm 0.03) \cdot 10^{-3}$	0
ORCA upgoing $T_0 \pm 1$ day	1.2°	$3.5 \cdot 10^{-4}$	$(2.7 \pm 0.3) \cdot 10^{-3}$	0
ORCA downgoing $T_0 \pm 1$ day	1.0°	$1.7 \cdot 10^{-5}$	$(2.7 \pm 0.3) \cdot 10^{-3}$	0
ORCA downgoing $T_0[-50\text{s}, +5000\text{s}]$	5.4°	$6.9 \cdot 10^{-8}$	$(2.7 \pm 0.3) \cdot 10^{-3}$	0

Table 1: Results of the analyses performed, both for KM3NeT ARCA and ORCA searches. The RoI used in each search is shown, together with the expected number of background and signal events. No candidate event has been found inside the ON region for any of the searches.

Since we are dealing with a transient event, it is also interesting to set an UL on the radiant fluence which is defined as the energy flux (per flavour) integrated over a certain emission period of interest. It can be computed as

$$\mathcal{F}^{\text{UL}} = \Delta T \int_{E_{min}}^{E_{max}} E\Phi_0^{\text{UL}} \left(\frac{E}{E_0}\right)^{-\gamma} dE, \tag{2}$$

where ΔT is the time window covered, E_0 is a reference energy level, in our case 1 GeV, and E_{min} and E_{max} correspond respectively to the 5% and 95% energy quantiles in the energy range of the detectable neutrino flux. The UL results for the six searches performed are provided in Table 2.

These results can be compared with the ones obtained by the IceCube Neutrino Observatory in similar searches. Figure 2 shows an adaptation of Figure 1 in [15], where the results from the present contribution have been added alongside the ones of IceCube. In concrete, ULs on $E^2F(E) = \Delta T \times \Phi_0^{UL}$, the energy-scaled per-flavour neutrino flux, integrated in time, have been computed to include the results in the mentioned figure. Only the ULs derived for a $\gamma = 2$ spectral index are shown. Note that a direct comparison is not straightforward, as each UL is computed according to different time window assumptions. The results derived in these searches are coherent with the ones obtained by IceCube, considering that we have worked with partial configurations of both KM3NeT detectors.

5. Conclusions

In this contribution, we have summarised the results of the offline search for neutrino emission from GRB 221009A performed using KM3NeT data. This analysis, together with the ones presented in [18], represents the first multi-messenger study performed by the KM3NeT Collaboration. Moreover, this is the first analysis where data from ARCA in the 21-line configuration, and ORCA in the 10-line one, have been analyzed.

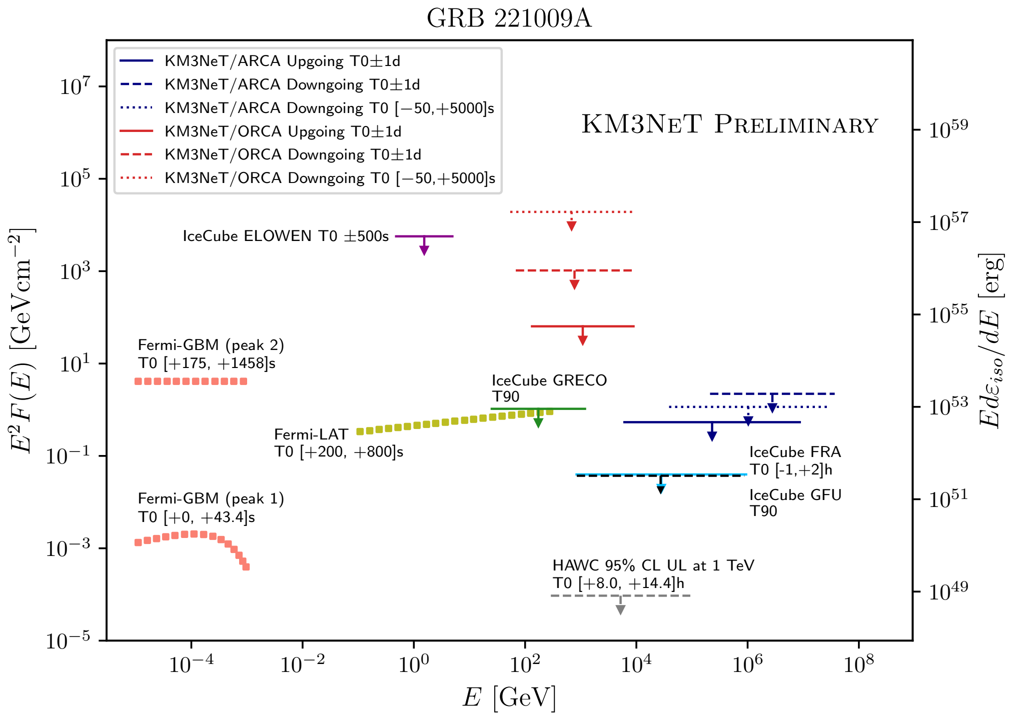

Figure 2: Comparison of the upper limits derived for IceCube and KM3NeT on the energy-scaled time-integrated neutrino emission from GRB 221009A (left y-axis), together with several gamma-ray observations. The right y-axis shows the differential isotropic equivalent energy. All the neutrino ULs shown are derived for a $\gamma = 2$ spectral index. This figure has been adapted from Figure 1 in [15], incorporating the results obtained in this contribution. More information about the IceCube results and the electromagnetic results can be consulted in [15].

ANALYSIS	Φ_0 UL [GeV^{-1}cm^{-2}s^{-1}]	5% energy quantile	95% energy quantile	Radiant fluence $\mathcal{F}^{UL}$ [GeVcm^{-2}]	$E^2F(E)$ UL [GeVcm^{-2}]
ARCA upgoing $T_0 \pm 1$ day	$6.2 \cdot 10^{-6}$	6.1 TeV	8.7 PeV	7.8	$5.4 \cdot 10^{-1}$
ARCA downgoing $T_0 \pm 1$ day	$2.6 \cdot 10^{-5}$	211.1 TeV	36.8 PeV	22.6	2.2
ARCA downgoing $T_0[-50s, +5000s]$	$2.3 \cdot 10^{-4}$	38.8 TeV	27.3 PeV	7.6	1.2
ORCA upgoing $T_0 \pm 1$ day	$7.4 \cdot 10^{-4}$	133 GeV	9.8 TeV	$5.4 \cdot 10^{2}$	$6.4 \cdot 10^{1}$
ORCA downgoing $T_0 \pm 1$ day	$1.6 \cdot 10^{-2}$	68 GeV	8.8 TeV	$1.3 \cdot 10^{4}$	$1.0 \cdot 10^{3}$
ORCA downgoing $T_0[-50s, +5000s]$	3.8	54 GeV	8.7 TeV	$9.8 \cdot 10^{4}$	$1.9 \cdot 10^{4}$

Table 2: UL results in the neutrino emission from GRB 221009A for the analyses performed, both for KM3NeT ARCA and ORCA. $\mathcal{F}^{UL}$ stands for the energy-integrated per-flavour neutrino flux integrated over the emission period, while $E^2F(E)$ represents the energy-scaled per-flavour neutrino flux, also integrated in time. The 90% sensitivity energy range is also provided. Note that in the case of KM3NeT/ARCA, the energy range goes up to the few PeV range.

Despite no neutrino candidate has been found, upper limits have been set in the flux normalization factor and in the fluence neutrino emission of GRB 221009A. The next step is to reduce the latency of this kind of search and be able to introduce typically offline features (dynamic calibrations, UL computations, etc.) in the online follow-ups. For that purpose, the KM3NeT Online Framework [17] will include analysis methods derived from this contribution.

References

[1] https://gcn.gsfc.nasa.gov/gcn3/32636.gcn3.
[2] https://gcn.gsfc.nasa.gov/gcn3/32632.gcn3.
[3] LHAASO collaboration, Science, 380 6652 1390-1396 (2023).
[4] https://gcn.gsfc.nasa.gov/gcn3/32658.gcn3.
[5] https://gcn.gsfc.nasa.gov/gcn3/32648.gcn3.
[6] T. Laskar et al., *Astrophys. J. Lett.* **946** (2023) L23.
[7] https://gcn.gsfc.nasa.gov/gcn3/32686.gcn3.
[8] M. Shrestha et al., *Astrophys. J. Lett.* **946** (2023) L25 [2302.03829].
[9] https://gcn.gsfc.nasa.gov/gcn3/32756.gcn3.
[10] https://gcn.gsfc.nasa.gov/gcn3/32660.gcn3.
[11] https://gcn.gsfc.nasa.gov/gcn3/32683.gcn3.
[12] "NASA, General Coordinates Network." https://gcn.nasa.gov/.
[13] A. Rudolph, M. Petropoulou, W. Winter, and v. Bošnjak, *Astrophys. J. Lett.* **944** (2023) L34.
[14] https://gcn.gsfc.nasa.gov/gcn3/32665.gcn3.
[15] IceCube collaboration, *Astrophys. J. Lett.* **946** (2023) L26.
[16] https://gcn.gsfc.nasa.gov/gcn3/32741.gcn3.
[17] S. Celli et al., for the KM3NeT Collaboration, PoS (ICRC 2023) 1125 (2023).
[18] J. Palacios González et al., for the KM3NeT Collaboration PoS (ICRC 2023) 1521 (2023).
[19] KM3NeT collaboration, *J. Phys. G* **43** (2016) 084001.
[20] KM3NeT collaboration, *JINST* **17** (2022) P07038.
[21] C. Gatius Oliver et al., for the KM3NeT Collaboration PoS (ICRC 2023) 1033 (2023).
[22] T. P. Li and Y. Q. Ma, *Astrophys. J.* **272** (1983) 317.
[23] T. Chen and C. Guestrin in *Proceedings of the 22nd acm sigkdd international conference on knowledge discovery and data mining*, pp. 785–794, 2016.
[24] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57** (1998) 3873.

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], 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)1503