PROCEEDINGS OF SCIENCE

Improving the description of atmospheric muons in KM3NeT data using the Daemonflux data-driven model

---

Brían Ó Fearraigh,[a,*] **Venugopal Ellajosyula,**[a,b] **Andrey Romanov**[c] **and Vladimir Kulikovskiy**[a,b] **on behalf of the KM3NeT Collaboration**

[a] *Istituto Nazionale di Fisica Nucleare, INFN Sezione di Genova,*
Via Dodecaneso 33, 16146, Genova, Italy

[b] *Dipartimento di Fisica, Università degli Studi di Genova,*
Via Dodecaneso 33, 16146, Genova, Italy

[c] *LPC CAEN, Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, 6 boulevard Maréchal Juin, 14050, Caen, France*

E-mail: `ofearrai@ge.infn.it`, `vellajosyula@km3net.de`, `vladimir.kulikovskiy@ge.infn.it`, `romanov@lpccaen.in2p3.fr`

The Cubic Kilometre Neutrino Telescope - KM3NeT - is subject to an intense flux of atmospheric muons, even at the bottom of the Mediterranean Sea. These atmospheric muons are created by the collisions of cosmic rays with nuclei of the upper atmosphere and their subsequent interactions, and as such, serve as probes of cosmic ray physics. The KM3NeT/ARCA and KM3NeT/ORCA detectors are located offshore Portopalo di Capo Passero, Italy, and Toulon, France, respectively, at corresponding depths of 3.5 km and 2.45 km below sea level. They offer the unique ability to detect atmospheric muons at two different locations and depths, as part of the same research infrastructure. The KM3NeT Collaboration has presented results comparing the flux of atmospheric muons in the detector with CORSIKA simulations, and - by showing an underestimation of the muon data by the simulation - is contributing to the global phenomenon known as the Muon Puzzle. A data-driven model Daemonflux has recently appeared on the scene and shows promise of alleviating this discrepancy. In this study, Daemonflux is incorporated into the atmospheric muon simulation used to describe KM3NeT data, and its impact in doing so is estimated. We also evaluate the impact of the optical properties of the seawater on the agreement between the KM3NeT data and the atmospheric muon simulation.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

---

[*] Speaker

1. Introduction

KM3NeT is a research infrastructure under construction in the Mediterranean Sea [1]. Although predominantly designed for neutrino physics and astronomy studies, KM3NeT actively participates in the field of cosmic ray physics. The high-energy (TeV and above) atmospheric muons that reach the detector at its Mediterranean depths come from the earliest part of the cosmic ray air shower interaction, offering the opportunity to probe this stage of the air shower development.

An outstanding problem in physics is referred to as the ‘Muon Puzzle’ [2]. This describes the phenomenon where, across a compilation of measurements from various detectors worldwide, there exists a discrepancy between cosmic ray air shower simulations and the data. The various hadronic interaction models which act as input to the simulations are believed to be the source of the discrepancy. Such models describe the formation and evolution of the hadronic component of the air shower, and its resulting atmospheric muon production; hence, a fundamental understanding of the physics of the hadronic interactions is lacking. Studies carried out by the KM3NeT Collaboration show that KM3NeT itself also falls victim to the Muon Puzzle, with a reported deficit ranging from 40% to 80% between atmospheric muon data and simulation [3].

A novel development in this investigation is the use of a ‘data-driven’ hadronic interaction model, namely ‘Daemonflux’ [4], to address this discrepancy. Daemonflux consists of a combination of atmospheric lepton fluxes computed with the Global Spline Fit (GSF) cosmic ray flux model [5] and the Data-Driven hadronic interaction Model (DDM) [6], the latter being a collection of fits to particle yields from fixed target accelerators. The GSF and DDM parameters are then calibrated to muon data in order to obtain a description of the data from various experiments. The resulting flux model incorporates competitively-low flux uncertainties.

A recent study by the KM3NeT Collaboration re-weighted the atmospheric muon simulation software CORSIKA [8] according to the Daemonflux model, and showed an improvement in the description of the atmospheric muon data by the simulation [7]. The discrepancy shown in [3] is reduced to below 20% maximum across the two KM3NeT detectors of ORCA-6 and ARCA-6, through a re-scaling of the distributions. Note that the nomenclature of ARCA/ORCA-X in this study denotes the number of associated detection units X in either detector, as described in the following section.

Another simulation tool utilised within KM3NeT is MUPAGE [9, 10]. This software quickly provides the flux of atmospheric muons at depths underwater or in-ice, according to a specific parameterisation. The goal of this particular study is to incorporate the Daemonflux-related event weights of [7] into the MUPAGE parameterisation, for a much quicker yet reliable description of the atmospheric muon data used within KM3NeT. The new parameterisation is then compared to data for the larger KM3NeT detectors of ARCA-21 and ORCA-13.

2. The KM3NeT Infrastructure

KM3NeT consists of two detectors in the Mediterranean Sea, located at the different aforementioned depths and locations. The ARCA detector is designed to search for astrophysical neutrinos and to discover their sources, whilst ORCA will focus on neutrino oscillation research: determining the yet-unknown neutrino mass ordering and precisely measuring neutrino oscillation parameters.

The technology is based on the principle of instrumenting a large volume of seawater with tens of thousands of photomultiplier tubes (PMTs). Thirty-one PMTs are contained within a pressure-resistant glass sphere of diameter ∼ 43.2 cm, which, alongside power, processing, and read-out electronics, form a 'digital optical module' [11]. Between two Dyneema® ropes, 18 optical modules are attached at repeating distances to form a 'detection unit' (DU). These are deployed at sea level, attached to a seafloor network of electronic circuitry and optical fibres, and suspended vertically through their own buoyancy and with the aid of additional buoys. KM3NeT envisages 115 DUs in ORCA upon completion, and a corresponding 230 in ARCA. The three-dimensional arrangement of the optical modules, i.e. their recurring distances along the ropes and the horizontal distance between them, is different between the two detectors. This optimises the same technology for the different neutrino energy ranges of interest to either detector.

The PMTs are used to detect the Cherenkov radiation which results from the relativistic products of neutrino interactions in the vicinity of the detector. By instrumenting a large, three-dimensional volume, and through the use of nanosecond-timing resolution and precise position calibration, the digitised signals from the particle interactions are used to determine the energy and direction of the incident neutrinos. Subject to a continuous rate of atmospheric muons coming from above, the KM3NeT detectors also capture the signals from atmospheric muons in the same way. Such signals form >99% of the recorded data.

The KM3NeT DUs are being deployed in phases, resulting in different detector configurations. For example, this work includes data from six DUs of both ORCA and ARCA. These are referred to as the ORCA-6 and ARCA-6 detectors. At present, KM3NeT operates 33 DUs at the ARCA site and 28 DUs at the ORCA site.

3. MUPAGE Atmospheric Muon Simulation

MUPAGE is a fast atmospheric muon bundle generator, which describes distributions of the single and multi-muon bundle flux, single and multi-muon bundle energy, and the lateral spread of the muon bundles from the bundle axis, using parametric equations. These equations are valid for depths underwater or within ice from 1–5 km w.e., for a zenith angle from 0° (completely down-going) to 85°, and by default are parameterised according to a full Monte Carlo (MC) air shower simulation. The free parameters within the MUPAGE software can be varied in order to further improve the description of KM3NeT data. Such efforts to 'tune' MUPAGE to data or detailed CORSIKA simulations have previously been carried out by the KM3NeT Collaboration [3, 12].

Most relevant to this work are the single muon flux parameterisation within MUPAGE. For the single muon flux ϕ, of multiplicity $m = 1$, at depth h, and zenith angle θ [9, 10]:

$$\phi(m = 1; h, \theta) = K(h, \theta) = K_0(h) \cos\theta \cdot e^{K_1(h) \cdot \sec\theta} , \tag{1}$$

with

$$K_0(h) = K_{0a} \cdot h^{K_{0b}} , \tag{2}$$

$$K_1(h) = K_{1a} \cdot h + K_{1b} . \tag{3}$$

Additionally, the multiple-muon flux is governed by parameters denoted within MUPAGE as ν, and the lateral spread denoted by R. A description of these parameters can be found within [9, 10].

4. Tuning MUPAGE to Daemonflux-weighted CORSIKA simulations

4.1 Daemonflux event weights

In this work, MUPAGE is tuned to CORSIKA-simulated distributions of the atmospheric muon energy and zenith angle at different depths below sea level. The distributions have been re-weighted to incorporate the Daemonflux model, as obtained from [7]. These weights, and thus the following tuning procedure, are only valid for single muons i.e. muon bundles of multiplicity = 1. This is because Daemonflux does not currently allow for a separate treatment of muon bundle multiplicity. The weights are obtained separately for μ^+ and μ^-, using a 2-D linear interpolation of the zenith angle and energy of the muon with the highest energy at sea level.

4.2 Tuning Procedure

The tuning procedure is the same as carried out in [3], and uses the same CORSIKA simulations as detailed within that work. Five different primaries of hydrogen, carbon, oxygen, helium, and iron are used to describe the atmospheric muon flux at sea level, for the energy ranges of TeV–PeV muons. The GSF model is used for the cosmic ray mass and composition; the atmospheric density profile and hadronic interaction models are detailed therein, the latter of which includes the use of Sibyll 2.3d [13]. These muons are then propagated to different depths from 2–3.5 km below sea level in steps of 250 m, using the PROPOSAL software [14]. The same energy loss processes and seawater composition accounted for in [3] are also used.

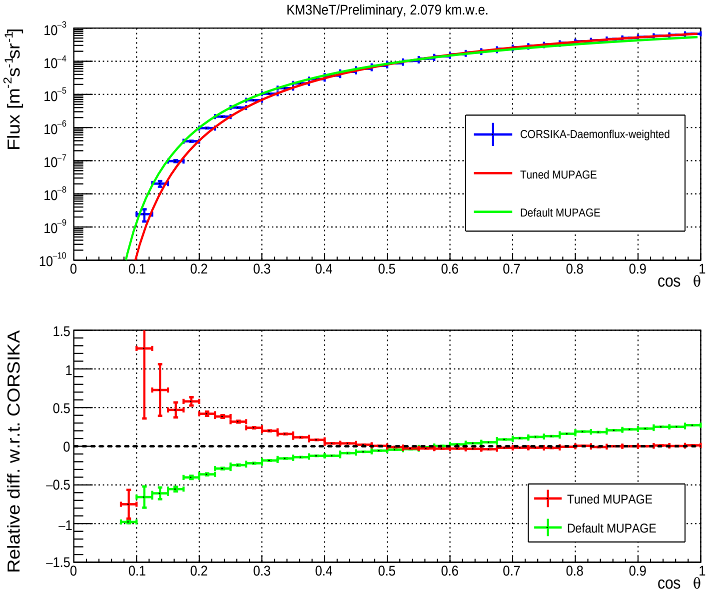


Figure 1: Top figure: An example from the MUPAGE tuning fit procedure, at a vertical depth of 2.079 km w.e., where a fit (in red) of the MUPAGE single muon flux parameters is made to CORSIKA-simulated data (blue). CORSIKA has been weighted by the Daemonflux weights described in text. The default MUPAGE function is also shown (green). Bottom figure: The relative difference with respect to the CORSIKA-Daemonflux-weighted data for the default MUPAGE flux function is compared to the relative difference for the fitted MUPAGE function.

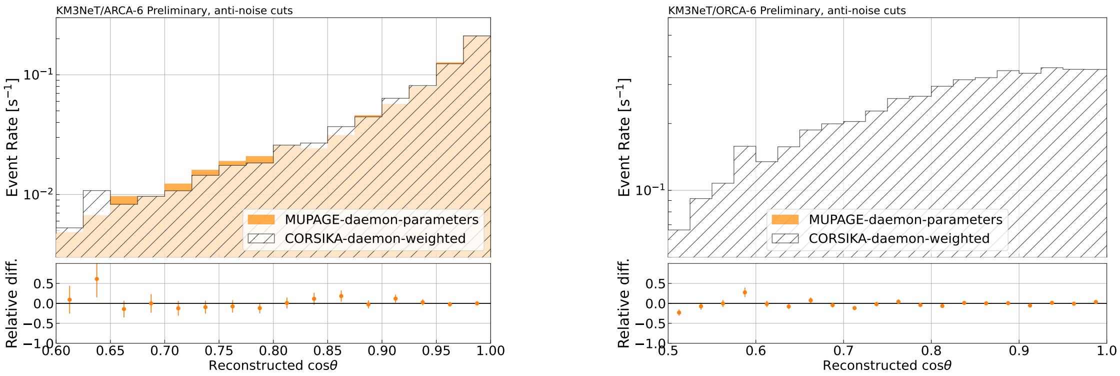
The fit to the single muon flux is carried out for each of the seven depths, where the flux as a function of the zenith angle is found for CORSIKA data re-weighted to Daemonflux, and Eqn. 1 is fitted to it, giving values of K_0 and K_1. A fit is then performed to the new values of these parameters separately, where e.g. a fit is made to the values of K_0 as a function of the depth, in order to determine K_{0a} and K_{0b}. One such result from the fit procedure is shown in Figure 1.

The same procedure was carried out for the single muon energy spectrum, as parameterised by MUPAGE. However, for this fit it was concluded that the nominal MUPAGE values describe the energy distribution from CORSIKA better than from the fit procedure, in particular at muon energies above the TeV scale. The default and new values of the K parameters are shown in Table 1.

MUPAGE parameter	tuned value	default value
K0a	0.01374	0.0072
K0b	-2.1073	1.927
K1a	-0.5873	0.581
K1b	-0.2346	0.034

Table 1: List of tuned and default MUPAGE values, following the tuning procedure described in the text.

4.3 Comparison of tuned MUPAGE to Daemonflux-weighted CORSIKA



(a) **(b)**

Figure 2: The reconstructed $\cos\theta$ of single muon events from the tuned MUPAGE parameterisation and the CORSIKA simulation, weighted according to the Daemonflux events weights. The distributions and the relative difference (of MUPAGE with respect to CORSIKA-Dameonflux-weighted) are shown for the (a) ARCA-6 and (b) ORCA-6 detectors. The anti-noise cuts are described in the text.

As a means of validating the tuning procedure, a sample of 1,000,000 muons is generated according to the new K parameterisation with MUPAGE. Both this MUPAGE-generated event sample, and the CORSIKA events used in the study of [7], weighted by the Daemonflux event weights, are propagated through the detector simulation chain. For a brief description of this chain: the light induced by particle events in the detector is propagated and the PMT response is simulated, the events are filtered through trigger algorithms to select physical events of interest, and the events are reconstructed under the hypothesis of a muon track or particle shower inducing light in the detector [1]. The comparison of the cosine of the reconstructed zenith angles of muon events is illustrated in Figure 2, for the ARCA-6 and ORCA-6 detectors. The presented ranges are chosen based on the phase space in either detector in which the direction of events is well-reconstructed.

Noise can originate from bioluminescence in the seawater and radioactive decays in the water and optical module glass, resulting in recorded signals that may survive the trigger algorithms. Basic cuts to remove this noise are included here, where a value of the reconstructed likelihood quality and the number of recorded hits in the detector are required. Only single muon events are shown. The MUPAGE parameterisation reproduces the CORSIKA-weighted-by-Daemonflux distribution sufficiently, accounting for statistical fluctuations. Any slight disagreement between the tuned MUPAGE simulation and CORSIKA is not considered a systematic uncertainty in this work.

5. Comparing a New MUPAGE Parameterisation to recent KM3NeT data

5.1 Finalised MUPAGE Parameterisation

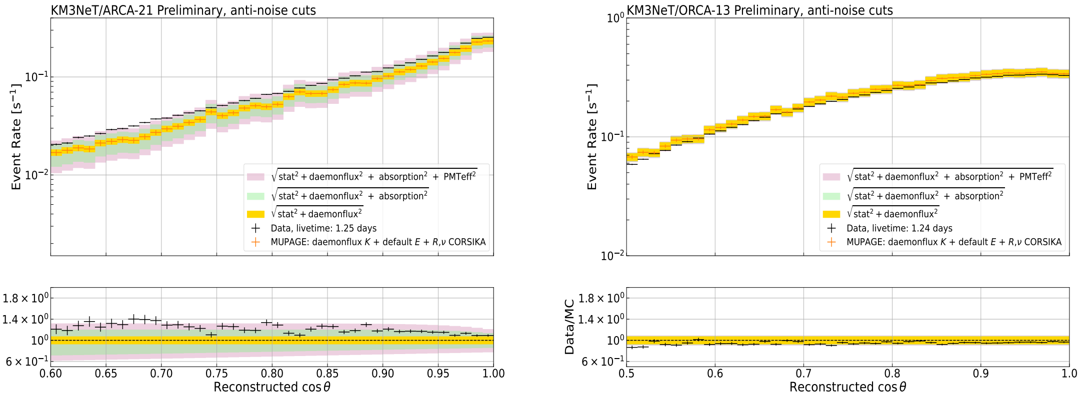
Altering the K parameters alone in MUPAGE results in an overestimation of the data - and the simulated muon multiplicity - compared to the default MUPAGE parameters. This is due to the tuning being valid for single muons only, whereas muon bundles of multiplicity > 1 are not accounted for.

In order to address this, various MUPAGE parameterisations are tested in their agreement with data and their effect on the multiplicity distribution. The most physically-motivated parameterisation is chosen: the K values which incorporate the Daemonflux weighting, the default single muon energy parameters, and the remaining parameters which come from the aforementioned KM3NeT study [3], which tuned MUPAGE to CORSIKA data in the same methodology. The parameters used in the tuned-on-CORSIKA study of [3] result in an improved description of the data at higher energies and replicate the multiplicity distribution from CORSIKA itself. The tuned-on-CORSIKA parameters use the default multiple muon energy values, and new values of the multiple-muon lateral spread R and flux ν. This MUPAGE parameterisation is henceforth referred to as 'MUPAGE daemonflux K + default E + R,ν CORSIKA'.

5.2 Data-MC Comparison

As recorded by ARCA-21 and ORCA-13, data from 10 periods of data-taking are selected from the respective detectors. These data comply with high-quality criteria and have been sufficiently calibrated. Muon events are generated according to the MUPAGE daemonflux K + default E + R,ν CORSIKA parameterisation. The simulated events are processed through the simulation chain to the reconstruction level following a 'run-by-run' approach, where the exact data-taking conditions such as PMT rates, detector geometry, trigger algorithm criteria etc. are accounted for.

The data and simulated events according to the new MUPAGE parameterisation are shown in Figure 3 for the ARCA-21 and ORCA-13 detectors. The contributions from the systematic uncertainties are included. The data-MC discrepancy is at the maximum level of ~40% for ARCA-21 and < 10% for ORCA-13.



(a) **(b)**

Figure 3: The MUPAGE parameterisation, tuned on a combination of CORSIKA and CORSIKA re-weighted according to Daemonflux, is illustrated (in orange) alongside data (in black) from the KM3NeT experiment, for the (a) ARCA-21 and (b) ORCA-13 detectors. The rate of events, as well as the ratio of the MC simulation to the data, is shown. The contributions from the statistical ('stat') and systematic uncertainties from Daemonflux, the absorption length and PMT efficiencies are displayed as error bands, added in quadrature.

5.3 Systematic Uncertainty Evaluation

The main systematic uncertainties associated with the rate of atmospheric muons in the detectors are shown in Figure 3, and added in quadrature. Daemonflux itself has an associated uncertainty. Another is the current understanding of the optical properties of water; namely, the knowledge on the absorption length of light in seawater at the two different KM3NeT detector sites. Another uncertainty arises from the light detection efficiency of the PMTs in the infrastructure. A thorough explanation of these uncertainties can be found in [3].

From [7], a flat 7% error is conservatively used here as the uncertainty from Daemonflux. As a reminder the uncertainty within Daemonflux itself is data-driven (from sea-level data, not below). For the light absorption length and PMT efficiency, these two simulation inputs are separately altered by ±10%, and the ratio of the upper and lower limits compared to the standard simulation (i.e. the new MUPAGE parameterisation, in this case) is used to extract uncertainty estimates.

In ARCA-21, the absorption length and PMT detection efficiency contribute greatly towards the uncertainty on the measurement of the atmospheric muon rate. Of note is that for ORCA-13, the Daemonflux uncertainty captures almost the entire data-MC disagreement.

5.4 Concluding Remarks

A new atmospheric muon flux parameterisation is introduced, developed through a tuning procedure on CORSIKA simulations, which incorporates the Daemonflux model. This parameterisation is compared with atmospheric muon data for the KM3NeT detectors, with evaluated systematic uncertainties. Through the inclusion of Daemonflux, this result attempts to address the long-standing issue of the underestimation of data by atmospheric muon simulations - forming part of the Muon Puzzle landscape - and reduces the flux uncertainties to a single systematic error.

References

[1] S. Adrian-Martinez *et al.* [KM3Net], "Letter of intent for KM3NeT 2.0" J. Phys. G **43** (2016), 084001 doi:10.1088/0954-3899/43/8/084001 [arXiv:1601.07459].

[2] J. Albrecht, L. Cazon, H. Dembinski, A. Fedynitch, K. H. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan and R. Ulrich, *et al.* Astrophys. Space Sci. **367** (2022) no.3, 27 doi:10.1007/s10509-022-04054-5 [arXiv:2105.06148 [astro-ph.HE]].

[3] S. Aiello *et al.* [KM3NeT], Eur. Phys. J. C **84** (2024) no.7, 696 doi:10.1140/epjc/s10052-024-13018-8 [arXiv:2403.11946 [astro-ph.HE]].

[4] J. P. Yañez and A. Fedynitch, Phys. Rev. D **107** (2023) no.12, 123037 doi:10.1103/PhysRevD.107.123037 [arXiv:2303.00022 [hep-ph]].

[5] H. P. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn and T. Stanev, PoS **ICRC2017** (2018), 533 doi:10.22323/1.301.0533 [arXiv:1711.11432 [astro-ph.HE]].

[6] A. Fedynitch and M. Huber, Phys. Rev. D **106** (2022) no.8, 083018 doi:10.1103/PhysRevD.106.083018 [arXiv:2205.14766 [astro-ph.HE]].

[7] V. Ellajosyula [KM3NeT], PoS **PIC2024** (2024)In Publication

[8] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz and T. Thouw, FZKA-6019.

[9] G. Carminati, A. Margiotta and M. Spurio, "Atmospheric MUons from PArametric formulas: A Fast GEnerator for neutrino telescopes (MUPAGE)" Comput. Phys. Commun. **179** (2008), 915 doi:10.1016/j.cpc.2008.07.014 [arXiv:0802.0562].

[10] Y. Becherini, A. Margiotta, M. Sioli and M. Spurio, "A Parameterisation of single and multiple muons in the deep water or ice" Astropart. Phys. **25** (2006), 1 doi:10.1016/j.astropartphys.2005.10.005 [arXiv:hep-ph/0507228].

[11] S. Aiello *et al.* [KM3NeT], JINST **17** (2022), P07038 doi:10.1088/1748-0221/17/07/P07038 [arXiv:2203.10048 [astro-ph.IM]].

[12] B. Ó Fearraigh [KM3NeT], PoS **ICRC2021** (2021), 1176 doi:10.22323/1.395.1176

[13] F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev, Phys. Rev. D **102** (2020) no.6, 063002 doi:10.1103/PhysRevD.102.063002 [arXiv:1912.03300 [hep-ph]].

[14] J. H. Koehne, K. Frantzen, M. Schmitz, T. Fuchs, W. Rhode, D. Chirkin and J. Becker Tjus, Comput. Phys. Commun. **184** (2013), 2070-2090 doi:10.1016/j.cpc.2013.04.001

Full Authors List: The KM3NeT Collaboration

O. Adriani[b,a], A. Albert[c,be], A.R. Alhebsi[d], S. Alshalloudi[d], M. Alshamsi[e], S. Alves Garre[f], F. Ameli[g], M. Andre[h], L. Aphecetche[i], M. Ardid[j], S. Ardid[j], J. Aublin[k], F. Badaracco[m,l], L. Bailly-Salins[n], B. Baret[k], A. Bariego-Quintana[f], M. Barnard[o], Y. Becherini[k], M. Bendahman[p], F. Benfenati Gualandi[r,q], M. Benhassi[s,p], D.M. Benoit[t], Z. Beňušová[v,u], E. Berbee[w], E. Berti[b], V. Bertin[e], P. Betti[b], S. Biagi[x], M. Boettcher[o], D. Bonanno[x], M. Bondì[y], S. Bottai[b], A.B. Bouasla[bf], J. Boumaaza[z], M. Bouta[e], M. Bouwhuis[w], C. Bozza[aa,p], R.M. Bozza[ab,p], H. Brânzaş[ac], F. Bretaudeau[i], M. Breuhaus[e], R. Bruijn[ad,w], J. Brunner[e], R. Bruno[y], E. Buis[w,ae], R. Buompane[s,p], I. Burriel[f], J. Busto[e], B. Caiffi[m], D. Calvo[f], A. Capone[g,af], F. Carenini[r,q], V. Carretero[ad,w], T. Cartraud[k], P. Castaldi[ag,q], V. Cecchini[f], S. Celli[g,af], L. Cerisy[e], M. Chabab[ah], A. Chen[ai], S. Cherubini[aj,x], T. Chiarusi[q], W. Chung[ak], M. Circella[al], R. Clark[am], R. Cocimano[x], J.A.B. Coelho[k], A. Coleiro[k], A. Condorelli[k], R. Coniglione[x], P. Coyle[e], A. Creusot[k], G. Cuttone[x], R. Dallier[i], A. De Benedittis[s,p], G. De Wasseige[am], V. Decoene[i], P. Deguire[e], I. Del Rosso[r,q], L.S. Di Mauro[x], I. Di Palma[g,af], A.F. Díaz[an], D. Diego-Tortosa[x], C. Distefano[x], A. Domi[ao], C. Donzaud[k], D. Dornic[e], E. Drakopoulou[ap], D. Drouhin[c,be], J.-G. Ducoin[e], P. Duverne[k], R. Dvornický[v], T. Eberl[ao], E. Eckerová[v,u], A. Eddymaoui[z], T. van Eeden[w], M. Eff[k], D. van Eijk[w], I. El Bojaddaini[aq], S. El Hedri[k], S. El Mentawi[e], V. Ellajosyula[m], A. Enzenhöfer[e], M. Farino[ak], G. Ferrara[aj,x], M. D. Filipović[ar], F. Filippini[q], D. Franciotti[x], L.A. Fusco[aa,p], T. Gal[ao], J. García Méndez[j], A. Garcia Soto[f], C. Gatius Oliver[w], N. Geißelbrecht[ao], E. Genton[am], H. Ghaddari[aq], L. Gialanella[s,p], B.K. Gibson[t], E. Giorgio[x], I. Goos[k], P. Goswami[k], S.R. Gozzini[f], R. Gracia[ao], B. Guillon[n], C. Haack[ao], C. Hanna[ak], H. van Haren[as], E. Hazelton[ak], A. Heijboer[w], L. Hennig[ao], J.J. Hernández-Rey[f], A. Idrissi[x], W. Idrissi Ibnsalih[p], G. Illuminati[q], R. Jaimes[f], O. Janik[ao], D. Joly[e], M. de Jong[at,w], P. de Jong[ad,w], B.J. Jung[w], P. Kalaczyński[bg,au], U.F. Katz[ao], J. Keegans[t], V. Kikvadze[av], G. Kistauri[aw,av], C. Kopper[ao], A. Kouchner[ax,k], Y. Y. Kovalev[ay], L. Krupa[u], V. Kueviakoe[w], V. Kulikovskiy[m], R. Kvatadze[aw], M. Labalme[n], R. Lahmann[ao], M. Lamoureux[am], A. Langella[ak], G. Larosa[x], C. Lastoria[n], J. Lazar[am], A. Lazo[f], G. Lehaut[n], V. Lemaître[am], E. Leonora[y], N. Lessing[f], G. Levi[r,q], M. Lindsey Clark[k], F. Longhitano[y], S. Madarapu[f], F. Magnani[e], L. Malerba[m,l], F. Mamedov[u], A. Manfreda[p], A. Manousakis[az], M. Marconi[l,m], A. Margiotta[r,q], A. Marinelli[ab,p], C. Markou[ap], L. Martin[i], M. Mastrodicasa[af,g], S. Mastroianni[p], J. Mauro[am], K.C.K. Mehta[au], G. Miele[ab,p], P. Migliozzi[p], E. Migneco[x], M.L. Mitsou[s,p], C.M. Mollo[p], L. Morales-Gallegos[s,p], N. Mori[b], A. Moussa[aq], I. Mozun Mateo[n], R. Muller[q], M.R. Musone[s,p], M. Musumeci[x], S. Navas[ba], A. Nayerhoda[al], C.A. Nicolau[g], B. Nkosi[ai], B. Ó Fearraigh[m], V. Oliviero[ab,p], A. Orlando[x], E. Oukacha[k], L. Pacini[b], D. Paesani[x], J. Palacios González[f], G. Papalashvili[al,av], P. Papini[b], V. Parisi[l,m], A. Parmar[n], C. Pastore[al], A. M. Păun[ac], G.E. Păvălaş[ac], S. Peña Martínez[k], M. Perrin-Terrin[e], V. Pestel[n], M. Petropavlova[u,bh], P. Piattelli[x], A. Plavin[ay,bi], C. Poirè[aa,p], V. Popa†[2][ac], T. Pradier[c], J. Prado[f], S. Pulvirenti[x], C.A. Quiroz-Rangel[j], N. Randazzo[y], A. Ratnani[bb], S. Razzaque[bc], I.C. Rea[p], D. Real[f], G. Riccobene[x], J. Robinson[o], A. Romanov[l,m,n], E. Ros[ay], A. Šaina[f], F. Salesa Greus[f], D.F.E. Samtleben[at,w], A. Sánchez Losa[f], S. Sanfilippo[x], M. Sanguineti[l,m], D. Santonocito[x], P. Sapienza[x], M. Scaringella[b], M. Scarnera[am,k], J. Schnabel[ao], J. Schumann[ao], J. Seneca[w], P. A. Sevle Myhr[am], I. Sgura[al], R. Shanidze[av], Chengyu Shao[bj,e], A. Sharma[k], Y. Shitov[u], F. Šimkovic[v], A. Simonelli[p], A. Sinopoulou[y], B. Spisso[p], M. Spurio[r,q], O. Starodubtsev[b], D. Stavropoulos[ap], I. Štekl[u], D. Stocco[i], M. Taiuti[l,m], Y. Tayalati[z,bb], H. Thiersen[o], I. Tosta e Melo[y,aj], B. Trocmé[k], V. Tsourapis[ap], C. Tully[ak], E. Tzamariudaki[ap], A. Ukleja[au], A. Vacheret[n], V. Valsecchi[x], V. Van Elewyck[ax,k], G. Vannoye[l,m], E. Vannuccini[b], G. Vasileiadis[bd], F. Vazquez de Sola[w], A. Veutro[g,af], S. Viola[x], D. Vivolo[s,p], A. van Vliet[d], E. de Wolf[ad,w], I. Lhenry-Yvon[k], S. Zavatarelli[m], D. Zito[x], J.D. Zornoza[f], and J. Zúñiga[f].

[a]Università di Firenze, Dipartimento di Fisica e Astronomia, via Sansone 1, Sesto Fiorentino, 50019 Italy
[b]INFN, Sezione di Firenze, via Sansone 1, Sesto Fiorentino, 50019 Italy
[c]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[d]Khalifa University of Science and Technology, Department of Physics, PO Box 127788, Abu Dhabi, United Arab Emirates
[e]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[f]IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València), c/Catedrático José Beltrán, 2, 46980 Paterna, Valencia, Spain
[g]INFN, Sezione di Roma, Piazzale Aldo Moro, 2 - c/o Dipartimento di Fisica, Edificio, G.Marconi, 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]Subatech, IMT Atlantique, IN2P3-CNRS, Nantes Université, 4 rue Alfred Kastler - La Chantrerie, Nantes, BP 20722 44307 France
[j]Universitat Politècnica de València, Instituto de Investigación para la Gestión Integrada de las Zonas Costeras, C/ Paranimf, 1, Gandia, 46730 Spain
[k]Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[l]Università di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[m]INFN, Sezione di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[n]LPC CAEN, Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, 6 boulevard Maréchal Juin, Caen, 14050 France
[o]North-West University, Centre for Space Research, Private Bag X6001, Potchefstroom, 2520 South Africa
[p]INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[q]INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[r]Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy

---

[2] Deceased

[s]Università degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Matematica e Fisica, viale Lincoln 5, Caserta, 81100 Italy
[t]E. A. Milne Centre for Astrophysics, University of Hull, Hull, HU6 7RX, United Kingdom
[u]Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, Prague, 110 00 Czech Republic
[v]Comenius University in Bratislava, Department of Nuclear Physics and Biophysics, Mlynska dolina F1, Bratislava, 842 48 Slovak Republic
[w]Nikhef, National Institute for Subatomic Physics, PO Box 41882, Amsterdam, 1009 DB Netherlands
[x]INFN, Laboratori Nazionali del Sud, (LNS) Via S. Sofia 62, Catania, 95123 Italy
[y]INFN, Sezione di Catania, (INFN-CT) Via Santa Sofia 64, Catania, 95123 Italy
[z]University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[aa]Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[ab]Università di Napoli “Federico II”, Dip. Scienze Fisiche “E. Pancini”, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[ac]Institute of Space Science - INFLPR Subsidiary, 409 Atomistilor Street, Magurele, Ilfov, 077125 Romania
[ad]University of Amsterdam, Institute of Physics/IHEF, PO Box 94216, Amsterdam, 1090 GE Netherlands
[ae]TNO, Technical Sciences, PO Box 155, Delft, 2600 AD Netherlands
[af]Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy
[ag]Università di Bologna, Dipartimento di Ingegneria dell’Energia Elettrica e dell’Informazione "Guglielmo Marconi", Via dell’Università 50, Cesena, 47521 Italia
[ah]Cadi Ayyad University, Physics Department, Faculty of Science Semlalia, Av. My Abdellah, P.O.B. 2390, Marrakech, 40000 Morocco
[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", (INFN-CT) Via Santa Sofia 64, Catania, 95123 Italy
[ak]Princeton University, Department of Physics, Jadwin Hall, Princeton, New Jersey, 08544 USA
[al]INFN, Sezione di Bari, via Orabona, 4, Bari, 70125 Italy
[am]UCLouvain, Centre for Cosmology, Particle Physics and Phenomenology, Chemin du Cyclotron, 2, Louvain-la-Neuve, 1348 Belgium
[an]University of Granada, Department of Computer Engineering, Automation and Robotics / CITIC, 18071 Granada, Spain
[ao]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Straße 2, 91058 Erlangen, Germany
[ap]NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attikis, Athens, 15310 Greece
[aq]University Mohammed I, Faculty of Sciences, BV Mohammed VI, B.P. 717, R.P. 60000 Oujda, Morocco
[ar]Western Sydney University, School of Science, Locked Bag 1797, Penrith, NSW 2751 Australia
[as]NIOZ (Royal Netherlands Institute for Sea Research), PO Box 59, Den Burg, Texel, 1790 AB, the Netherlands
[at]Leiden University, Leiden Institute of Physics, PO Box 9504, Leiden, 2300 RA Netherlands
[au]AGH University of Krakow, Al. Mickiewicza 30, 30-059 Krakow, Poland
[av]Tbilisi State University, Department of Physics, 3, Chavchavadze Ave., Tbilisi, 0179 Georgia
[aw]The University of Georgia, Institute of Physics, Kostava str. 77, Tbilisi, 0171 Georgia
[ax]Institut Universitaire de France, 1 rue Descartes, Paris, 75005 France
[ay]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[az]University of Sharjah, Sharjah Academy for Astronomy, Space Sciences, and Technology, University Campus - POB 27272, Sharjah, - United Arab Emirates
[ba]University of Granada, Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., 18071 Granada, Spain
[bb]School of Applied and Engineering Physics, Mohammed VI Polytechnic University, Ben Guerir, 43150, Morocco
[bc]University of Johannesburg, Department Physics, PO Box 524, Auckland Park, 2006 South Africa
[bd]Laboratoire Univers et Particules de Montpellier, Place Eugène Bataillon - CC 72, Montpellier Cédex 05, 34095 France
[be]Université de Haute Alsace, rue des Frères Lumière, 68093 Mulhouse Cedex, France
[bf]Université Badji Mokhtar, Département de Physique, Faculté des Sciences, Laboratoire de Physique des Rayonnements, B. P. 12, Annaba, 23000 Algeria
[bg]AstroCeNT, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rektorska 4, Warsaw, 00-614 Poland
[bh]Charles University, Faculty of Mathematics and Physics, Ovocný trh 5, Prague, 116 36 Czech Republic
[bi]Harvard University, Black Hole Initiative, 20 Garden Street, Cambridge, MA 02138 USA

Acknowledgements

The authors acknowledge the financial support of: KM3NeT-INFRADEV2 project, funded by the European Union Horizon Europe Research and Innovation Programme under grant agreement No 101079679; Funds for Scientific Research (FRS-FNRS), Francqui foundation, BAEF foundation. Czech Science Foundation (GAČR 24-12702S); 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, Normandy Region (Alpha, Blue-waves and Neptune), France, The Provence-Alpes-Côte d’Azur Delegation for Research and Innovation (DRARI), the Provence-Alpes-Côte d’Azur region, the Bouches-du-Rhône Departmental Council, the Metropolis of Aix-Marseille Provence and the City of Marseille through the

CPER 2021-2027 NEUMED project, The CNRS Institut National de Physique Nucléaire et de Physique des Particules (IN2P3); Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-22-13708), Georgia; This research was funded by the European Union (ERC MuSES project No 101142396); The General Secretariat of Research and Innovation (GSRI), Greece; Istituto Nazionale di Fisica Nucleare (INFN) and Ministero dell'Università e della Ricerca (MUR), through PRIN 2022 program (Grant PANTHEON 2022E2J4RK, Next Generation EU) and PON R&I program (Avviso n. 424 del 28 febbraio 2018, Progetto PACK-PIR01 00021), Italy; IDMAR project Po-Fesr Sicilian Region az. 1.5.1; A. De Benedittis, W. Idrissi Ibnsalih, M. Bendahman, A. Nayerhoda, G. Papalashvili, I. C. Rea, A. Simonelli have been supported by the Italian Ministero dell'Università e della Ricerca (MUR), Progetto CIR01 00021 (Avviso n. 2595 del 24 dicembre 2019); KM3NeT4RR MUR Project National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 3.1, Funded by the European Union – NextGenerationEU,CUP I57G21000040001, Concession Decree MUR No. n. Prot. 123 del 21/06/2022; 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 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; The program: "Excellence initiative-research university" for the AGH University in Krakow; The ARTIQ project: UMO-2021/01/2/ST6/00004 and ARTIQ/0004/2021; Ministry of Education and Scientific Research, Romania; Slovak Research and Development Agency under Contract No. APVV-22-0413; Ministry of Education, Research, Development and Youth of the Slovak Republic; MCIN for PID2021-124591NB-C41, -C42, -C43 and PDC2023-145913-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", for ASFAE/2022/014 and ASFAE/2022 /023 with funding from the EU NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana, for Grant AST22_6.2 with funding from Consejería de Universidad, Investigación e Innovación and Gobierno de España and European Union - NextGenerationEU, for CSIC-INFRA23013 and for CNS2023-144099, Generalitat Valenciana for CIDEGENT/2020/049, CIDEGENT/2021/23, CIDEIG/2023/20, ESGENT2024/24, CIPROM/2023/51, GRISOLIAP/2021/192 and INNVA1/2024/110 (IVACE+i), Spain; Khalifa University internal grants (ESIG-2023-008, RIG-2023-070 and RIG-2024-047), United Arab Emirates; The European Union's Horizon 2020 Research and Innovation Programme (ChETEC-INFRA - Project no. 101008324).

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.