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Sensitivity study for the prompt component in the atmospheric muon flux with KM3NeT detectors

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The network of two next-generation underwater Cherenkov neutrino telescopes: ARCA and ORCA is being successively deployed in the Mediterranean Sea by the KM3NeT Collaboration. The focus of ARCA is neutrino astronomy, while ORCA is mainly dedicated to neutrino oscillation studies. Both detectors are already operational in their intermediate states and collect valuable results. This work explores the potential of intermediate as well as complete detector configurations of ARCA and ORCA to observe the prompt component of the atmospheric muon flux, originating from cosmic ray interactions. It builds upon a dedicated reconstruction of observables characteristic for events composed of multiple muons, called muon bundles. The obtained results show that KM3NeT is sensitive to the prompt muon flux component and should be able to verify its existence within the first few years of data taking with completed detectors.

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

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

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PoS(ICRC2025)1071

1. Introduction

The KM3NeT research infrastructure is being built at the bottom of the Mediterranean Sea. Its two neutrino detectors: ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss) are located offshore Portopalo di Capo Passero, Sicily, Italy, at a depth of 3500 m and offshore Toulon, France, at a depth of 2450 m, respectively.

The main goal of ARCA is to observe TeV-PeV neutrinos from astrophysical sources or in coincidence with e.g. gravitational waves, gamma-ray bursts or blazar flares. The ORCA detector studies atmospheric neutrino oscillations at GeV energies, with the aim of determining the neutrino mass ordering [1].

Both detectors consist of vertically aligned detection units (DUs), each carrying 18 digital optical modules (DOMs) [2]. Every DOM houses 31 3-inch photomultiplier tubes (PMTs), calibration and positioning instruments, and readout electronics boards. ARCA and ORCA differ in the horizontal (90 m and 20 m respectively) and vertical (36 m and 9 m respectively) spacing between the DOMs, which is optimised for the energy ranges mentioned above. In this work, detectors in intermediate (6 DUs) and full building block (115 DUs) configurations are considered.

Atmospheric muons are the dominant signal in neutrino telescopes and a major background for the physics analyses with neutrinos; however, they also prove useful in testing the detector performance and validity of the simulations. Moreover, muon data contains valuable information about the extensive air showers (EAS) forming in the Earth's atmosphere and the primary cosmic rays (CRs) that cause them. At muon energies above the PeV-scale, a contribution from muons created by early decaying heavy hadrons (often containing the charm quark), called prompt muons, is expected. It has not been experimentally confirmed yet. The sensitivities of the KM3NeT detectors to the prompt muon flux are presented in Sec. 3.2.

2. Analysed data

The study presented in Sec. 3 uses a set of Monte Carlo (MC) simulations performed for four detector configurations, as summarised in Tab. 1. The number following the detector name indicates how many DUs are installed in a particular configuration. Each simulation is based on the common set of EAS generated with CORSIKA [3], with details given in Tab. 2. In [4], a more comprehensive description can be found, including information on comparisons with the other muon simulation code used within KM3NeT, MUPAGE [5] and with the experimental data collected in years 2020 and 2021. Each simulated EAS is associated with a muon bundle, i.e. a bunch of muons arriving almost simultaneously at the detector depth. Three potentially useful muon bundle observables are considered: the direction ($\cos\theta_{\mathrm{zenith}}$), the bundle energy E_{bundle}, and the muon multiplicity (number of muons in the bundle): N_{μ} [4, 6].

Table 1: Summary of the simulation statistics available for each of the four KM3NeT detector configurations.

Detector configuration	ARCA115	ARCA6	ORCA115	ORCA6
Number of events	4 489 177	1 215 552	4 825 073	1 923 475

Table 2: Compilation of CORSIKA simulation settings used to produce the MC samples used for this work.

CORSIKA version	HE hadronic model	Generated showers	$E_{\rm prim}$ range	Primaries
v7.7410	SIBYLL 2.3d [7]	$1.44 \cdot 10^{10}$	1 TeV–8 EeV	p, He, C, O, Fe

Atmosphere	Magnetic field	Assumed CR flux
Custom fit to MSIS-2.0 [8]	$B_x \simeq 25.22\,\mu$T, $B_z \simeq 38.48\,\mu$T	GST3 [9]

3. Prompt muon analysis

The atmospheric muon flux can be divided into two components: conventional muons, created primarily in decays of $\pi^{\pm}$ and $K^{\pm}$ and prompt muons originating from decays of shorter-lived hadrons. In the following, the potential of KM3NeT to observe the prompt muon flux is explored.

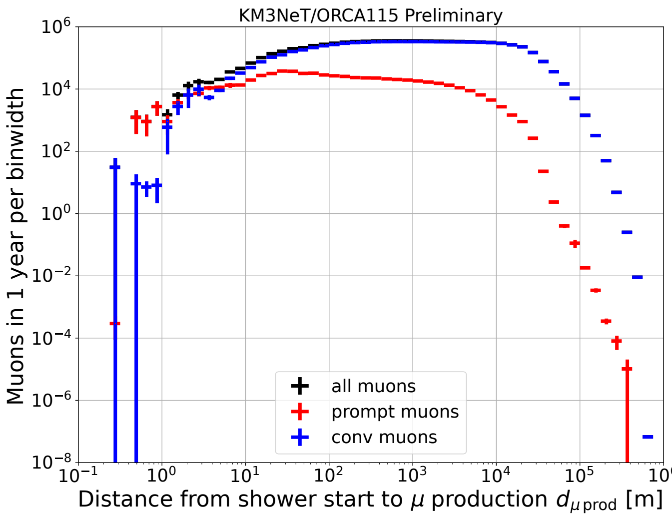
3.1 Adopted definitions

To construct a strict definition of a prompt muon, a criterion by which it is decided whether its parent particle counts as prompt is needed, with the most common choices being the lifetime or the decay length of the parent. Both parameters quantify how close to the first interaction point the muon is created. In this work, the threshold consistent with [10] is used, i.e. the lifetime of K-short $t_{K^0_S} = 89.5$ ps. In more complex scenarios, with decay chains preceding the creation of the muon, the decision is made to restrict the number of parent particles that allowed a muon to still be called prompt. This is motivated by two factors: longer chains mean longer distances travelled, and including longer chains would not be technically feasible due to the limitations of the CORSIKA MC simulation. In CORSIKA7, which was used here, only the mother and grandmother particle information is stored in the output [11]. This means that in the case where there are more than two parent particles, one could not exclude that one of them is conventional, e.g. a pion. Even though CORSIKA does not save the full parent particle lists, it is possible to infer their number from the hadronic and electromagnetic (EM) generation counters. Those counters are incremented after each interaction or decay, although not always by 1. For details, it is advisable to consult the documentation provided by the authors of CORSIKA [11, 12]. The summary of possible cases where a simulated muon is considered prompt is presented in Tab. 3. This definition is verified by investigating the distance at which muons are produced, which is presented in Fig. 1. Near the first interaction, there is an excess due to the prompt muons, which confirms this definition and its implementation as valid. The compilation of all simulated parent particles shown in Fig. 3 can be considered a further sanity check of the definition of the prompt component. It demonstrates that indeed most of the conventional muons originate from pion or kaon mothers, while the most substantial contributions to the prompt muon flux come from vector and D mesons.

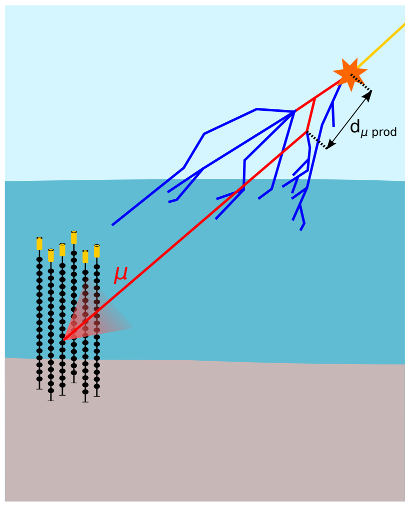
Since CORSIKA simulates EAS, the natural way to proceed is to consider the signal (SIG) and background (BGD) for the analysis at the level of muon bundles, not individual muons. SIG is defined as bundles with at least one prompt muon (according to the definition introduced above), and BGD would encompass bundles with zero prompt muons. TOTAL=SIG+BGD denotes all muon bundles combined. Generating a CORSIKA MC without the prompt component is not feasible, as production of only some of the contributing parent particles can be disabled (see the CHARM option

Table 3: Summary of potential scenarios in which the muon would be considered prompt. The cases when the grandmother is the same as the primary CR or when the mother is the same as the final muon indicate that there were less than three interactions/decays. h and e are the hadronic and electromagnetic generation counters, respectively. The mother particle and the muon have separate counters, hence there are two of each.

grandmother	mother	h_{mother}	h_μ	e_{mother}	e_μ
primary	μ	1	1	0	0
prompt	μ	any	any	0	0
primary	prompt	≤ 2	≤ 2	0	0
prompt	prompt	2 3	32 33	0	0



(a) Rate of atmospheric muons per year and bin width as a function of the distance between the first interaction of the primary and the point, where the muon was produced. The muon rate is computed for the ORCA115 (ORCA with 115 DUs installed) detector at reconstruction level.



(b) Sketch illustrating the meaning of the $d_{\mu\,\text{prod}}$ variable on an example of a prompt muon created after two subsequent decays and then observed by a detector composed of 6 DUs.

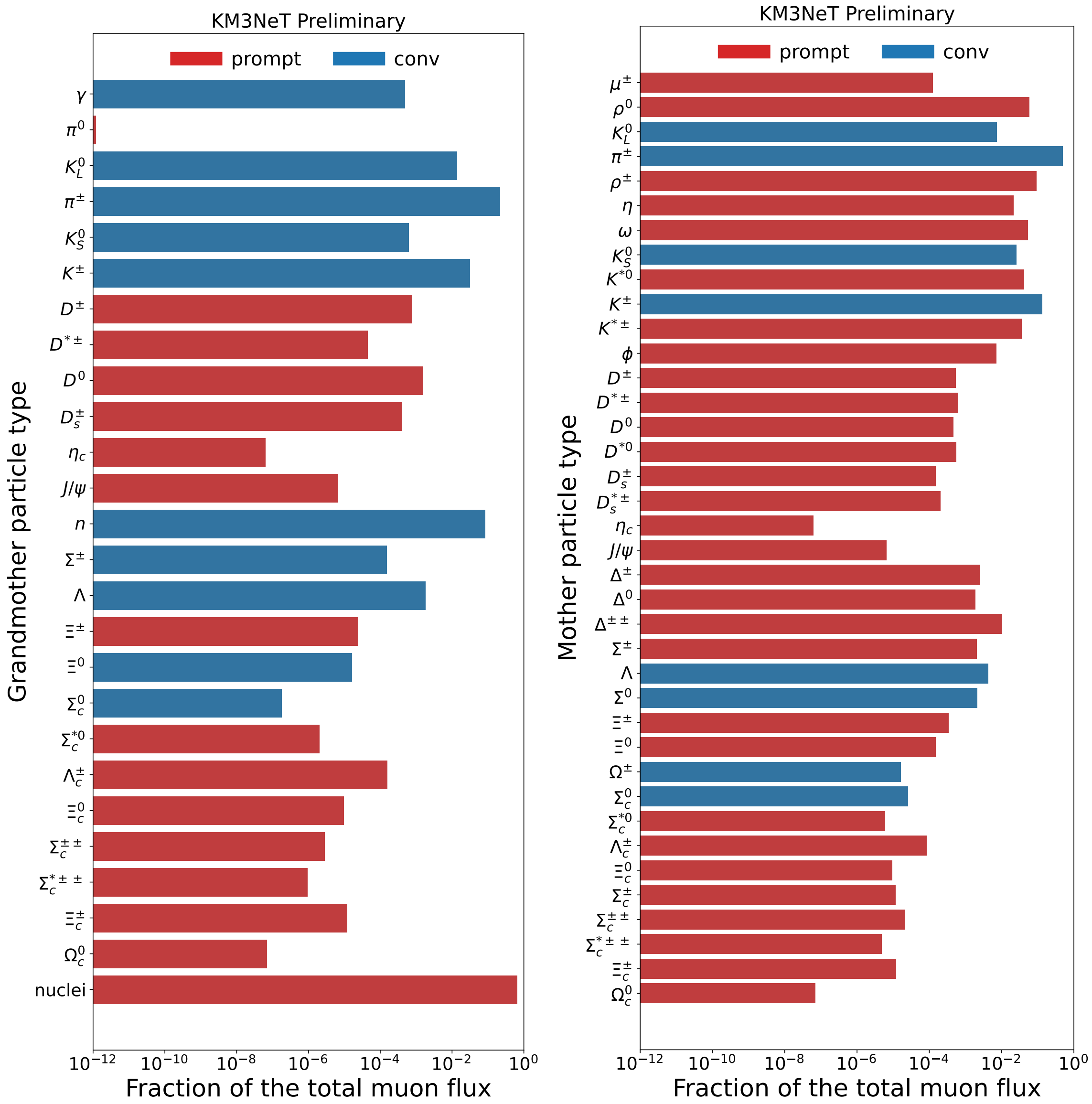
Figure 1: Demonstration of the adopted definition of prompt muons using the distance at which the muons are produced. Conventional is abbreviated as "conv".

in [12]). This means that BGD obtained just by selection from all simulated EAS is underestimated; it must be reweighted to compensate for discarded showers. This is done as a function of primary type and energy [4].

3.2 Methodology and results

The statistical test performed in this study consists in computing the Poissonian test statistic (TS) with a non-negligible uncertainty as

$$q_0 = \begin{cases} 2 \cdot \left[N_\text{T} \cdot \ln \left(\frac{N_\text{T} \cdot (N_\text{B} + \sigma_\text{B}^2)}{N_\text{B}^2 + N_\text{T} \cdot \sigma_\text{B}^2} \right) - \frac{N_\text{T}^2}{\sigma_\text{B}^2} \cdot \ln \left(1 + \frac{\sigma_\text{B}^2 (N_\text{T} - N_\text{B})}{N_\text{B} \cdot (N_\text{B} + \sigma_\text{B}^2)} \right) \right] & \text{for } \text{N}_\text{T} \geq \text{N}_\text{B} \\ 0 & \text{for } \text{N}_\text{T} < \text{N}_\text{B} \end{cases}, \qquad (1)$$



(a) Grandmother particles.

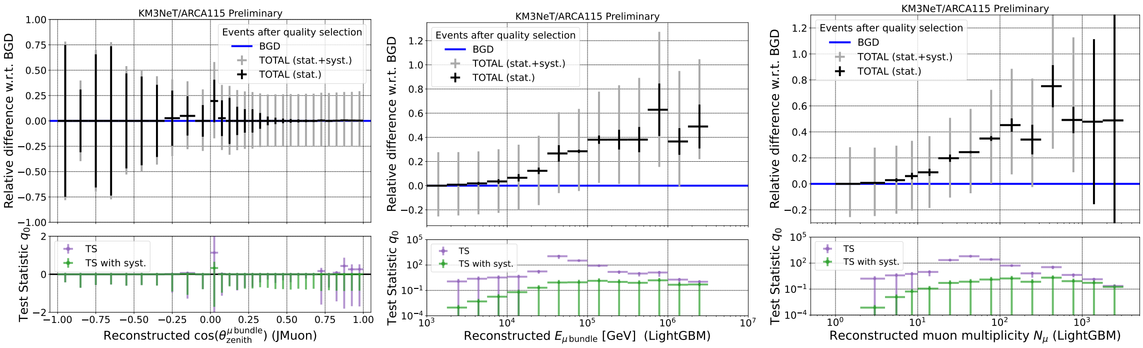
(b) Mother particles.

Figure 2: Overview of the classification of various parent particles as prompt or conventional (abbr. "conv"). In the plots, the particles and antiparticles are counted together, similarly for all the nuclei.

where T and B represent TOTAL and BGD, respectively. N is the number of events of one of the two categories and σ_B is the uncertainty on N_B. The formula in Eq. 1 follows from [13].

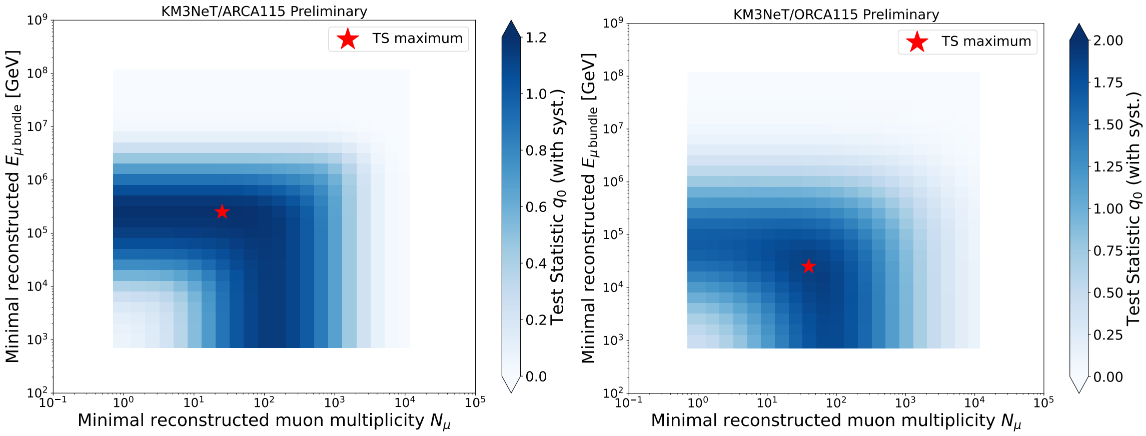
The distributions of muon bundle directions, energies, and multiplicities for BGD and TOTAL are compared in Fig. 3. There is no directional sensitivity; however, the energy and multiplicity distributions are clearly affected by the prompt muon flux, especially at $E_{\text{bundle}} \approx 50\,\text{PeV}$ and $N_\mu \approx 40$.

The final sensitivity calculation is performed on a single bin corresponding to the critical region where the test is most powerful. To optimise this region, a set of four 2D scans in $(N_\mu, E_{\text{bundle}})$



(a) Bundle direction. **(b)** Bundle energy. **(c)** Muon multiplicity.

Figure 3: Relative differences between TOTAL and BGD for reconstructed muon bundle direction (cosine of the zenith angle), bundle energy and muon multiplicity. In the lower panels, the TS values are reported in two variants: with and without the systematic uncertainty included. JMuon and LightGBM are two different reconstruction methods. Much more detail on the reconstruction as well as on the considered systematic uncertainties may be found in [4].

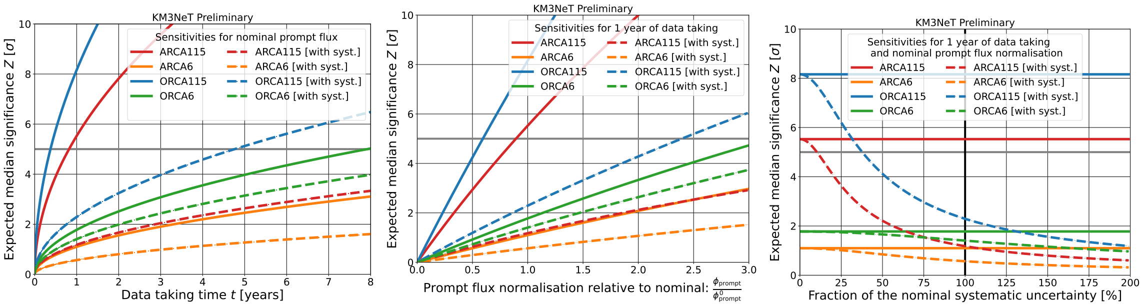


(a) ARCA115. **(b)** ORCA115.

Figure 4: Scans of minimal reconstructed muon multiplicities and bundle energies performed for ARCA115 and ORCA115. The optimal cuts are marked by red stars.

was performed, two for ARCA115 and two for ORCA115. The scans investigating the maximal values of both observables expectedly yield no upper limit; hence, they are not shown. The results for minimal energy and multiplicity are shown in Fig. 4. The resulting lower bounds of the critical regions are $N_\mu = 40$ for both detectors and $E_{\mathrm{bundle}} = 251$ TeV for ARCA115 and $E_{\mathrm{bundle}} = 16$ TeV for ORCA. To have a better comparability with the smaller detector configurations, the ARCA115 values are also used for ARCA6 and analogously between ORCA115 and ORCA6. This selection is combined with quality cuts derived from data vs MC comparisons for ARCA6 and ORCA6, described in [4].

After defining the critical regions and applying the quality cuts, the median expected significances for ARCA115, ARCA6, ORCA115, and ORCA6 were computed. They are reported in Fig. 5. No measurement of the prompt muon flux has been performed due to insufficient agreement



(a) $\sqrt{q_0}$ vs time. **(b)** $\sqrt{q_0}$ vs prompt normalisation. **(c)** $\sqrt{q_0}$ vs systematic uncertainty.

Figure 5: The sensitivities of four (colour-coded) KM3NeT detector configurations: ARCA115, ARCA6, ORCA115, and ORCA6 to exclude the BGD-only hypothesis. The expected median significance is computed as $\sqrt{q_0}$ (see Eq. 1). The solid lines show sensitivities computed only using the statistical uncertainty, while the dashed ones include both statistical and systematic uncertainties.

between the data and MC at lower energies [4].

4. Conclusions

KM3NeT shows sensitivity to confirming or rejecting the existence of the prompt muon flux, though it is clearly limited by systematic uncertainties. The situation is expected to improve with further direct measurements of the primary CR flux and more accurate models. More detailed simulations will also allow for a reduction in uncertainty on the detector side. Even at the current level of uncertainty, a complete ORCA or ARCA (note that in Fig. 5 the sensitivity of only one of the two building blocks of ARCA is shown) should be able to reach a $5\,\sigma$ significance in a few years of operation. This work did not consider combining the data from intermediate detector configurations, although this could naturally enable a sooner verification of the hypothesis, perhaps even before completion of the detectors. Such a combined analysis would pose quite a technical challenge, as it would require a separate CORSIKA simulation for each detector configuration.

Most of the effort is currently focused on improving the agreement between the data and MC, also for historical detector configurations. This includes reprocessing of the data as well as improvements in the simulation at various stages. In the case of KM3NeT simulations, a big milestone ahead is run-by-run MC productions, i.e. ones with specific conditions for each data-taking period (run). Up to now, CORSIKA has been used to produce time-averaged simulations because of computational constraints.

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Acknowledgements

This work was supported by the National Centre for Science: Poland grant 2021/41/N/ST2/01177; We gratefully acknowledge the funding support by program "Excellence initiative-research university" for the AGH University in Krakow as well as the ARTIQ project: UMO-2021/01/2/ST6/00004 and ARTIQ/0004/2021; 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;

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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 work is part of the MuSES project which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (grant agreement 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 Research, Innovation and Digitalisation, 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/2018/034, /2019/043, /2020/049, /2021/23, for CIDEIG/2023/20, for CIPROM/2023/51 and for GRISOLIAP/2021/192 and EU for MSC/101025085, 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).