

## Comparison of the measured atmospheric muon rate with Monte Carlo simulations and sensitivity study for detection of prompt atmospheric muons with KM3NeT

**Piotr Kalaczyński<sup>a,\*</sup> on behalf of the KM3NeT Collaboration**  
(a complete list of authors can be found at the end of the proceedings)

<sup>a</sup>National Centre for Nuclear Research,  
Pasteura 7, Warsaw, Poland  
E-mail: [piotr.kalaczynski@ncbj.gov.pl](mailto:piotr.kalaczynski@ncbj.gov.pl)

The KM3NeT Collaboration has successfully deployed the first detection units of the next generation undersea neutrino telescopes in the Mediterranean Sea at the two sites in Italy and in France. The data sample collected between December 2016 and January 2020 has been used to measure the atmospheric muon rate at two different depths under the sea level: 3.5 km with KM3NeT-ARCA and 2.5 km with KM3NeT-ORCA. Atmospheric muons represent an abundant signal in a neutrino telescope and can be used to test the reliability of the Monte Carlo simulation chain and to study the physics of extensive air showers caused by highly-energetic primary nuclei impinging the Earth's atmosphere. At energies above PeV the contribution from prompt muons, created right after the first interaction in the shower, is expected to become dominant, however its existence has not yet been experimentally confirmed. In this talk, data collected with the first detection units of KM3NeT are compared to Monte Carlo simulations based on MUPAGE and CORSIKA codes. The main features of the simulation and reconstruction chains are presented. Additionally, the first results of the simulated signal from the prompt muon component for KM3NeT-ARCA and KM3NeT-ORCA obtained with CORSIKA are discussed.

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\*Presenter

## 1. Introduction

KM3NeT is a research infrastructure under construction at the bottom of the Mediterranean Sea. It consists of two neutrino detectors: ARCA (Astroparticle Research with Cosmics in the Abyss) located off-shore Portopalo di Capo Passero, Sicily, Italy, at a depth of 3500 m and ORCA (Oscillation Research with Cosmics in the Abyss) off-shore Toulon, France, at a depth of 2450 m.

The main goal of ARCA is to detect TeV-PeV neutrinos from astrophysical sources or in coincidence with other high energy events, for example gravitational waves, gamma ray bursts or blazar flares. The ORCA detector will study oscillations of the atmospheric neutrinos in the GeV range, in order to determine the neutrino mass hierarchy (NMH) [1].

Both detectors have the same structure. They consist of vertically aligned detection units (DUs), each carrying 18 digital optical modules (DOMs) [1]. Each 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. Currently, both detectors are taking data with 6 DUs installed at each site. In final configurations, there will be 115 DUs at ORCA and 2x115 DUs (in two blocks) at ARCA site.

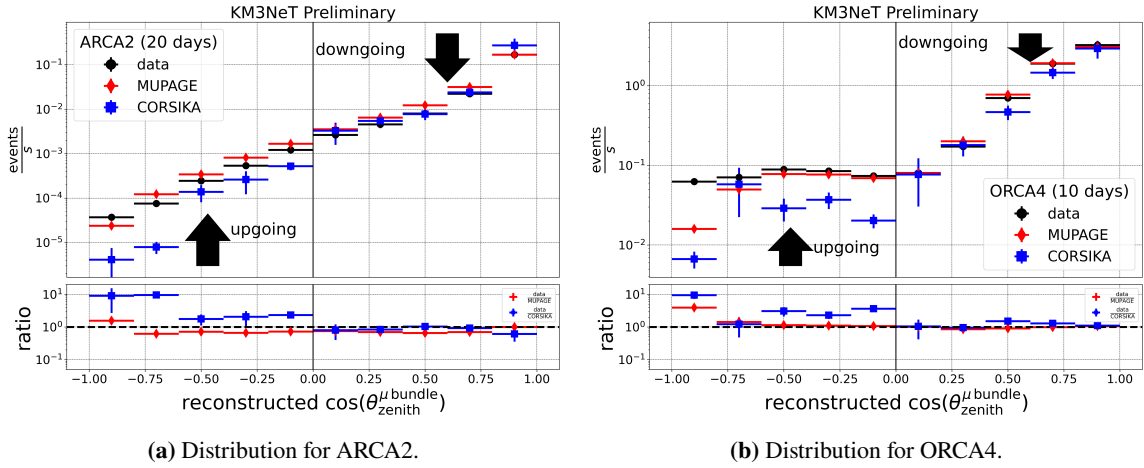
Atmospheric muons are the most abundant signal in a neutrino telescope and a major background to the physics analyses with neutrinos, however they also prove useful in testing the detector performance and validity of the simulations. In this paper, a comparison of the first data collected by ARCA and ORCA to the Monte Carlo (MC) simulations is presented.

Muon data contains valuable information about the extensive air showers (EAS) forming in the Earth's atmosphere and about the cosmic ray (CR) primaries that cause them. At muon energies above PeV, a contribution from muons created by quickly decaying heavy hadrons (often containing the charm quark), called prompt muons, is predicted. It has not been experimentally confirmed yet. The first results evaluating the expected signal due to the prompt muon contribution are shown in section 4. They are based on muon simulations for the full ARCA and ORCA detectors.

## 2. Muon simulation

The KM3NeT simulation chain is divided into several stages. The generation of the atmospheric muon bundles is performed using two different codes: MUPAGE [2] and CORSIKA [3]. MUPAGE is a fast simulation program, based on parametric formulas that generates muon bundles, induced by CRs impinging the Earth's atmosphere. The muon distributions are sampled on the surface of the active volume of the detector at different undersea depths and zenith angles. CORSIKA is a software package that simulates the interactions of the primary CRs in the upper atmosphere and follows the development of the shower to a specified observation level (here, it is the sea level). The CORSIKA package is flexible and allows to choose between different models to describe the hadronic interactions and the composition of the primary CR flux.

The GENIE-based code, gSeaGen [4, 5] is a multipurpose tool, commonly used in KM3NeT to simulate the neutrino interactions in the detectors. In this work, gSeaGen is used to convert the CORSIKA output into the KM3NeT standard format, compute event weights according to the specified CR composition model and propagate muon bundles from the sea level to the active



**Figure 1:** Rate of atmospheric muons as a function of the reconstructed zenith angle for data and MC simulation for the ARCA2 and ORCA4 detector. Most of the upgoing events (all MC events) are downgoing, but are badly reconstructed as upgoing. No quality cuts have been applied to remove the badly reconstructed tracks.

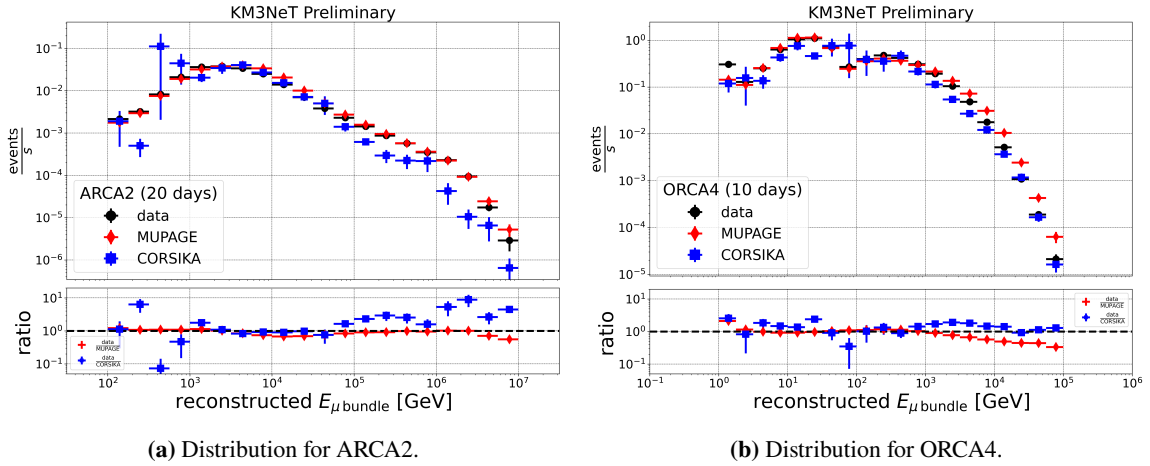
volume of the detector. The propagation is done using a 3-dimensional muon propagator, in this case: PROPOSAL [6]. This step is not necessary for MUPAGE, as it already generates events at the detector level.

After the propagation, Cherenkov light emission along the path of muons and their probability to be detected by the DOMs are simulated with a custom application developed for KM3NeT called JSirene, using multidimensional interpolation tables [7]. Subsequently, the following effects expected in the real data are also included in the simulated set: the environmental optical background due to the bioluminescence and the <sup>40</sup>K decay, detector response, taking into account the front-end electronics. For MUPAGE the simulation is performed in a run-by-run mode, which means that each data taking run is simulated separately. On the other hand, for CORSIKA a muon flux averaged over all runs is simulated. The same trigger algorithms as used for real data are applied to identify possible interesting events in the simulated sample [8]. Finally, the selected events are processed with the track reconstruction program "JGandalf", used for the real data stream as well [9]. At this stage the simulated MC events can be easily compared to the calibrated data. A track reconstruction algorithm is applied both to data and MC events.

### 3. Data vs MC comparisons

A sample of data collected with 2 DUs of the ARCA detector (ARCA2) from the 23th of December 2016 to the 2nd of March 2017 and with 4 DUs of the ORCA detector (ORCA4) from the 23th of July to 16th of December 2019 has been compared with the expectation from the MC based on the same triggering and reconstruction criteria (described in Section 2).

A sample of muon bundles with energies larger than 10 GeV and multiplicity up to 100 tracks was simulated with MUPAGE. The equivalent livetime is close to the considered detector livetime, about 20 days for ARCA2 and 10 days for ORCA4. The simulated MUPAGE events processed, as



**Figure 2:** Rate of atmospheric muons as a function of the reconstructed energy for data and MC simulation for the ARCA2 and ORCA4 detector. More details on the energy reconstruction can be found in [9].

described in Section 2, are shown in Figures 1 and 2 with the red marks. Only statistical errors are shown in the plots.

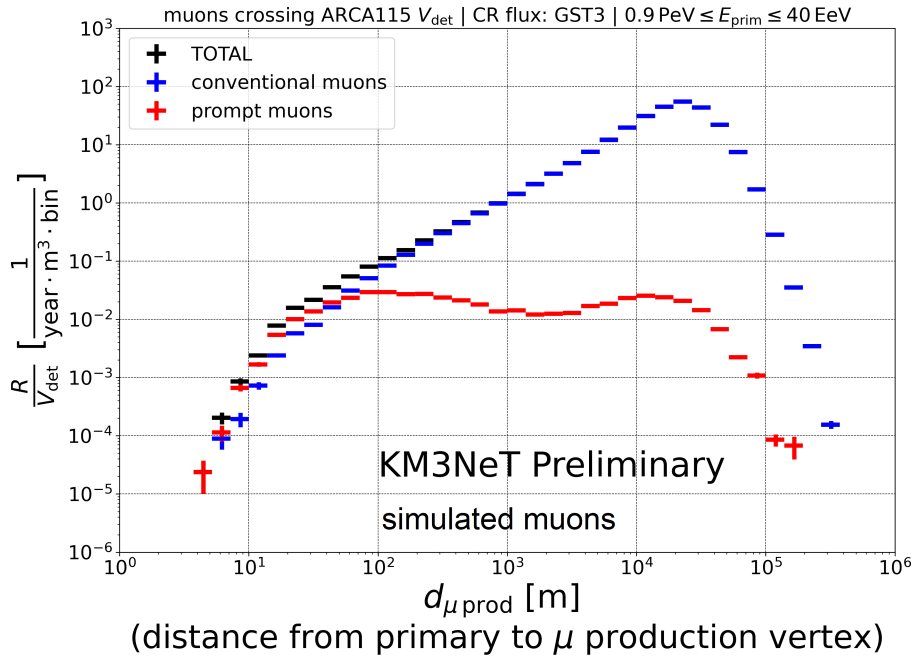
A total number of  $2.5 \cdot 10^9$  showers have been simulated with CORSIKA, using SIBYLL-2.3c to describe the high-energy hadronic interactions [10]. Five different species of nuclei were considered as primaries:  $p$ ,  $He$ ,  $C$ ,  $O$  and  $Fe$  with energies between 1 TeV and 1 EeV. The procedure presented in Section 2 has been followed and events were reconstructed with the same algorithm as for MUPAGE and experimental data. At the end, the events have been weighted according to the GST3 CR composition model [11]. The results of the CORSIKA simulation are shown as blue markers in Figures 1 and 2 and compared with data indicated as black points. The errors plotted are statistical only ( $\Delta x = \sqrt{\sum w_i^2}$ , where  $w_i$  is the weight of the  $i$ -th MC event). In all plots no systematic uncertainties are considered.

The early results presented here show that the used MC samples reproduce the data with reasonable level of agreement. The reconstructed upgoing muons in Figure 1 are misreconstructed downgoing muons. No quality cuts or selection have been applied to remove poorly reconstructed tracks. Note, that the systematic uncertainties, which have not been considered here, are expected to be larger than the statistical errors. The fact that the MC reproduces the shape of the data, confirms that the KM3NeT simulation chain is reliable and under control.

#### 4. Prompt muon analysis

The atmospheric muon flux is commonly divided into two categories: conventional muons, created mostly in  $\pi^\pm$  and  $K^\pm$  decays and prompt muons originating predominantly from decays of short-lived heavy hadrons. With this analysis, the potential of KM3NeT to observe the prompt muon flux is investigated.

The prompt sensitivity study is performed on a CORSIKA MC sample different than the one used for results of Section 3. The total number of simulated showers is  $5.3 \cdot 10^6$  and SIBYLL-2.3d is used for high-energy hadronic interactions [12]. Primary CR energies are simulated in the range



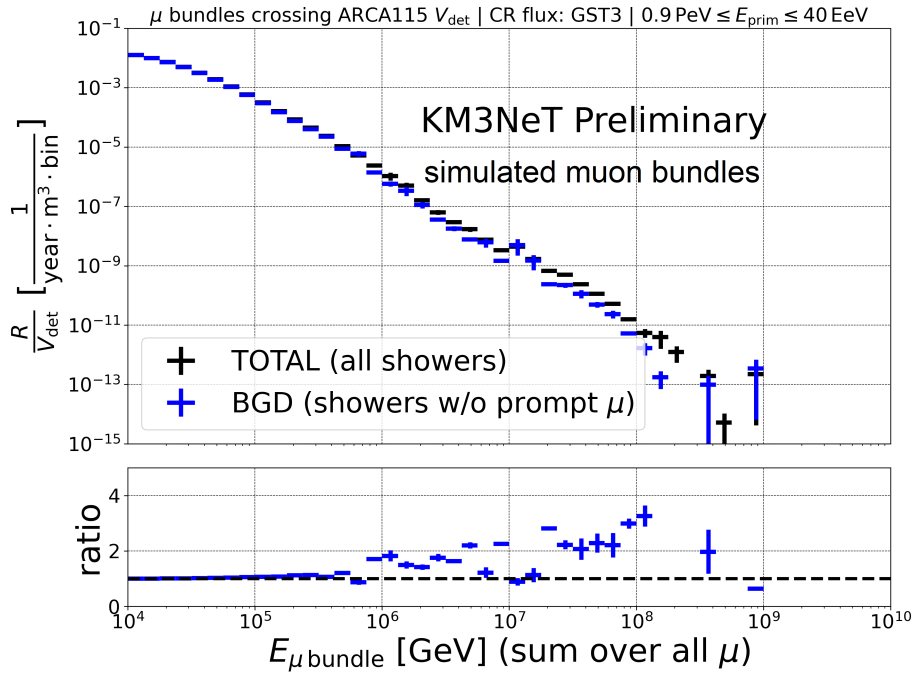
**Figure 3:** Rate of atmospheric muons per detector volume as a function of the distance between the first interaction of the primary and the point, where the muon was produced. The plot is done for ARCA115 detector based on the CORSIKA Monte Carlo at the detector level without light simulation, triggering or reconstruction.

from 0.9 PeV up to 40 EeV. Lower primary energies are not considered, since already PeV primaries will produce at most 10 TeV muons, which are well below the region, where the prompt muons are expected to start dominating. At these energies, they will be strongly overwhelmed by the conventional muon flux.

The prompt muon component was defined for the CORSIKA MC events based on two conditions: that all parent particles have lifetimes shorter than the one of  $K_S^0$  ( $8.95 \cdot 10^{-11}$  s) and that there are at most three generations of particles between the primary and the muon. This definition is tested in Figure 3, where it is shown how far from the interaction of the primary particle that started the shower, the muon is produced. Very close to the first interaction, there is indeed an excess coming from the prompt muons as expected, which confirms that the definition in use is sensible. The signal (SIG) for the analysis is defined to be muon bundles with at least one prompt muon (according to the introduced definition). Background (BGD) are the bundles with zero prompt muons and TOTAL denotes all muon bundles put together. The distributions of muon bundle energies for BGD and TOTAL are shown in figure 4 and there is a clear excess above BGD starting around 1 PeV, although difference is not large. This expected signal is promising and has to be verified at the reconstruction level.

## 5. Conclusions

With the first KM3NeT data, it is possible to compare the measured and the expected muon rate at ARCA and ORCA sites. The agreement between the data and MC is satisfactory and the



**Figure 4:** Rate of atmospheric muon bundles per detector volume as a function of the bundle energy (sum of energies of individual muons) for BGD and TOTAL for the ARCA115 detector.

simulation procedure provides reliable results. Nonetheless, there are ongoing efforts to further improve the description of the data. In the nearest future, the analysis will be repeated for data collected with the present configuration of the detectors: ARCA6 and ORCA6 (ARCA and ORCA each with six DUs installed) and using new MUPAGE and CORSIKA MC productions. A number of improvements is foreseen for the MC chain: optimisation of the muon propagation step, better definition of the geometry of muon propagation, a more accurate calculation of the event weights and addition of the contribution from delta rays to the energy reconstruction, to name a few. A systematic uncertainty study and an increase of the statistical significance of the sample, especially at the highest energies are planned for the CORSIKA MC.

The first results from the prompt muon sensitivity study are encouraging and suggest KM3NeT is sensitive to the prompt component. Figure 4 presents the expected result for ARCA115 (one building block of the ARCA detector, with 115 DUs). A similar behaviour has also been seen for ORCA115 simulation. A verification at the reconstruction level is necessary to ensure that detectors are efficient enough to extract the prompt signal. After the complete workflow of the analysis is established, comparison to the results of IceCube [13] is planned with the newest prompt muon flux models. Additionally, the muon multiplicity (observed number of muons in a bundle) has been found to be useful observable for the analysis and will be included to further boost the sensitivity.

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## Full Author List: KM3NeT Collaboration

M. Ageron<sup>1</sup>, S. Aiello<sup>2</sup>, A. Albert<sup>3,5,5</sup>, M. Alshamsi<sup>4</sup>, S. Alves Garre<sup>5</sup>, Z. Aly<sup>1</sup>, A. Ambrosone<sup>6,7</sup>, F. Ameli<sup>8</sup>, M. Andre<sup>9</sup>, G. Androulakis<sup>10</sup>, M. Anghinolfi<sup>11</sup>, M. Anguita<sup>12</sup>, G. Anton<sup>13</sup>, M. Ardid<sup>14</sup>, S. Ardid<sup>14</sup>, W. Assal<sup>1</sup>, J. Aublin<sup>4</sup>, C. Bagatelas<sup>10</sup>, B. Baret<sup>4</sup>, S. Basegmez du Pree<sup>15</sup>, M. Bendahman<sup>4,16</sup>, F. Benfenati<sup>17,18</sup>, E. Berbee<sup>15</sup>, A. M. van den Berg<sup>19</sup>, V. Bertin<sup>1</sup>, S. Beurthey<sup>1</sup>, V. van Beveren<sup>15</sup>, S. Biagi<sup>20</sup>, M. Billault<sup>1</sup>, M. Bissinger<sup>13</sup>, M. Boettcher<sup>21</sup>, M. Bou Cabo<sup>22</sup>, J. Boumaaza<sup>16</sup>, M. Bouta<sup>23</sup>, C. Boutonnet<sup>4</sup>, G. Bouvet<sup>24</sup>, M. Bouwhuis<sup>15</sup>, C. Bozza<sup>25</sup>, H.Brânzaş<sup>26</sup>, R. Bruijn<sup>15,27</sup>, J. Brunner<sup>1</sup>, R. Bruno<sup>2</sup>, E. Buis<sup>28</sup>, R. Buompane<sup>6,29</sup>, J. Busto<sup>1</sup>, B. Caiffi<sup>11</sup>, L. Caillat<sup>1</sup>, D. Calvo<sup>5</sup>, S. Campion<sup>30,8</sup>, A. Capone<sup>30,8</sup>, H. Carduner<sup>24</sup>, V. Carretero<sup>5</sup>, P. Castaldi<sup>17,31</sup>, S. Celli<sup>30,8</sup>, R. Cereseto<sup>11</sup>, M. Chabab<sup>32</sup>, C. Champion<sup>4</sup>, N. Chau<sup>4</sup>, A. Chen<sup>33</sup>, S. Cherubini<sup>20,34</sup>, V. Chiarella<sup>35</sup>, T. Chiarusi<sup>17</sup>, M. Circella<sup>36</sup>, R. Cocimano<sup>20</sup>, J. A. B. Coelho<sup>4</sup>, A. Coleiro<sup>4</sup>, M. Colomer Molla<sup>4,5</sup>, S. Colonges<sup>4</sup>, R. Coniglione<sup>20</sup>, A. Cosquer<sup>1</sup>, P. Coyle<sup>1</sup>, M. Cresta<sup>11</sup>, A. Creusot<sup>4</sup>, A. Cruz<sup>37</sup>, G. Cuttone<sup>20</sup>, A. D'Amico<sup>15</sup>, R. Dallier<sup>24</sup>, B. De Martino<sup>1</sup>, M. De Palma<sup>36,38</sup>, I. Di Palma<sup>30,8</sup>, A. F. Díaz<sup>12</sup>, D. Diego-Tortosa<sup>14</sup>, C. Distefano<sup>20</sup>, A. Domi<sup>15,27</sup>, C. Donzaud<sup>4</sup>, D. Dornic<sup>1</sup>, M. Dörr<sup>39</sup>, D. Drouhin<sup>3,5,5</sup>, T. Eberl<sup>13</sup>, A. Eddyamoui<sup>16</sup>, T. van Eeden<sup>15</sup>, D. van Eijk<sup>15</sup>, I. El Bojaddaini<sup>23</sup>, H. Eljarrari<sup>16</sup>, D. Elsaesser<sup>39</sup>, A. Enzenhöfer<sup>1</sup>, V. Espinosa<sup>14</sup>, P. Fermani<sup>30,8</sup>, G. Ferrara<sup>20,34</sup>, M. D. Filipović<sup>40</sup>, F. Filippini<sup>17,18</sup>, J. Fransen<sup>15</sup>, L. A. Fusco<sup>1</sup>, D. Gajanana<sup>15</sup>, T. Gal<sup>13</sup>, J. García Méndez<sup>14</sup>, A. Garcia Soto<sup>5</sup>, E. Garçon<sup>1</sup>, F. Garufi<sup>6,7</sup>, C. Gatiús<sup>15</sup>, N. Geißelbrecht<sup>13</sup>, L. Gialanella<sup>6,29</sup>, E. Giorgio<sup>20</sup>, S. R. Gozzini<sup>5</sup>, R. Gracia<sup>15</sup>, K. Graf<sup>13</sup>, G. Grella<sup>41</sup>, D. Guderian<sup>56</sup>, C. Guidi<sup>11,42</sup>, B. Guillon<sup>43</sup>, M. Gutiérrez<sup>44</sup>, J. Haefner<sup>13</sup>, S. Hallmann<sup>13</sup>, H. Hamdaoui<sup>16</sup>, H. van Haren<sup>45</sup>, A. Heijboer<sup>15</sup>, A. Hekalo<sup>39</sup>, L. Hennig<sup>13</sup>, S. Henry<sup>1</sup>, J. J. Hernández-Rey<sup>5</sup>, J. Hofestädt<sup>13</sup>, F. Huang<sup>1</sup>, W. Idrissi Ibsalih<sup>6,29</sup>, A. Ilioni<sup>4</sup>, G. Illuminati<sup>17,18,4</sup>, C. W. James<sup>37</sup>, D. Janezashvili<sup>46</sup>, P. Jansweijer<sup>15</sup>, M. de Jong<sup>15,47</sup>, P. de Jong<sup>15,27</sup>, B. J. Jung<sup>15</sup>, M. Kadler<sup>39</sup>, P. Kalaczyński<sup>48</sup>, O. Kalekin<sup>13</sup>, U. F. Katz<sup>13</sup>, F. Kayzel<sup>15</sup>, P. Keller<sup>1</sup>, N. R. Khan Chowdhury<sup>5</sup>, G. Kistauri<sup>46</sup>, F. van der Knaap<sup>28</sup>, P. Koosijman<sup>27,57</sup>, A. Kouchner<sup>4,49</sup>, M. Kreter<sup>21</sup>, V. Kulikovskiy<sup>11</sup>, M. Labalme<sup>43</sup>, P. Lagier<sup>1</sup>, R. Lahmann<sup>13</sup>, P. Lamare<sup>1</sup>, M. Lamoureux<sup>14</sup>, G. Larosa<sup>20</sup>, C. Lastoria<sup>1</sup>, J. Laurence<sup>1</sup>, A. Lazo<sup>5</sup>, R. Le Breton<sup>4</sup>, E. Le Guirriec<sup>1</sup>, S. Le Stum<sup>1</sup>, G. Lehaut<sup>43</sup>, O. Leonardi<sup>20</sup>, F. Leone<sup>20,34</sup>, E. Leonora<sup>2</sup>, C. Lerouvillos<sup>1</sup>, J. Lesrel<sup>4</sup>, N. Lessing<sup>13</sup>, G. Levi<sup>17,18</sup>, M. Lincetto<sup>1</sup>, M. Lindsey Clark<sup>4</sup>, T. Lipreau<sup>24</sup>, C. Llorens Alvarez<sup>14</sup>, A. Lonardo<sup>8</sup>, F. Longhitano<sup>2</sup>, D. Lopez-Coto<sup>44</sup>, N. Lumb<sup>1</sup>, L. Maderer<sup>4</sup>, J. Majumdar<sup>15</sup>, J. Mańczak<sup>5</sup>, A. Margiotta<sup>17,18</sup>, A. Marinelli<sup>6</sup>, A. Marini<sup>1</sup>, C. Markou<sup>10</sup>, L. Martin<sup>24</sup>, J. A. Martínez-Mora<sup>14</sup>, A. Martini<sup>35</sup>, F. Marzaioli<sup>6,29</sup>, S. Mastroianni<sup>6</sup>, K. W. Melis<sup>15</sup>, G. Miele<sup>6,7</sup>, P. Migliozzi<sup>6</sup>, E. Migneco<sup>20</sup>, P. Mijakowski<sup>48</sup>, L. S. Miranda<sup>50</sup>, C. M. Mollo<sup>6</sup>, M. Mongelli<sup>36</sup>, A. Moussa<sup>23</sup>, R. Müller<sup>15</sup>, P. Musico<sup>11</sup>, M. Musumeci<sup>20</sup>, L. Nauta<sup>15</sup>, S. Navas<sup>44</sup>, C. A. Nicolau<sup>8</sup>, B. Nkosi<sup>33</sup>, B. Ó Fearraigh<sup>15,27</sup>, M. O'Sullivan<sup>37</sup>, A. Orlando<sup>20</sup>, G. Ottonello<sup>11</sup>, S. Ottonello<sup>11</sup>, J. Palacios González<sup>5</sup>, G. Papalashvili<sup>46</sup>, R. Papaleo<sup>20</sup>, C. Pastore<sup>36</sup>, A. M. Páun<sup>26</sup>, G. E. Pávlaş<sup>26</sup>, G. Pellegrini<sup>17</sup>, C. Pellegrino<sup>18,58</sup>, M. Perrin-Terrin<sup>1</sup>, V. Pestel<sup>15</sup>, P. Piattelli<sup>20</sup>, C. Pieterse<sup>5</sup>, O. Pisanti<sup>6,7</sup>, C. Poiré<sup>14</sup>, V. Popa<sup>26</sup>, T. Pradier<sup>3</sup>, F. Pratalongo<sup>11</sup>, I. Probst<sup>13</sup>, G. Pühlhofer<sup>51</sup>, S. Pulvirenti<sup>20</sup>, G. Quémener<sup>43</sup>, N. Randazzo<sup>2</sup>, A. Rapicavoli<sup>34</sup>, S. Razaque<sup>50</sup>, D. Real<sup>5</sup>, S. Reck<sup>13</sup>, G. Riccobene<sup>20</sup>, L. Rigalleau<sup>24</sup>, A. Romanov<sup>11,42</sup>, A. Rovelli<sup>20</sup>, J. Royon<sup>1</sup>, F. Salesa Greus<sup>5</sup>, D. F. E. Samtleben<sup>15,47</sup>, A. Sánchez Losa<sup>36,5</sup>, M. Sanguineti<sup>11,42</sup>, A. Santangelo<sup>51</sup>, D. Santonocito<sup>20</sup>, P. Sapienza<sup>20</sup>, J. Schmelling<sup>15</sup>, J. Schnabel<sup>13</sup>, M. F. Schneider<sup>13</sup>, J. Schumann<sup>13</sup>, H. M. Schutte<sup>21</sup>, J. Seneca<sup>15</sup>, I. Sgura<sup>36</sup>, R. Shanidze<sup>46</sup>, A. Sharma<sup>52</sup>, A. Sinopoulou<sup>10</sup>, B. Spisso<sup>41,6</sup>, M. Spurio<sup>17,18</sup>, D. Stavropoulos<sup>10</sup>, J. Steijger<sup>15</sup>, S. M. Stellacci<sup>41,6</sup>, M. Taiuti<sup>11,42</sup>, F. Tatone<sup>36</sup>, Y. Tayalati<sup>16</sup>, E. Tenllado<sup>44</sup>, D. Tézier<sup>1</sup>, T. Thakore<sup>5</sup>, S. Theraube<sup>1</sup>, H. Thiersen<sup>21</sup>, P. Timmer<sup>15</sup>, S. Tingay<sup>37</sup>, S. Tsagkli<sup>10</sup>, V. Tsourapis<sup>10</sup>, E. Tzamariudaki<sup>10</sup>, D. Tzanetatos<sup>10</sup>, C. Valieri<sup>17</sup>, V. Van Elewyck<sup>4,49</sup>, G. Vasileiadis<sup>53</sup>, F. Versari<sup>17,18</sup>, S. Viola<sup>20</sup>, D. Vivolo<sup>6,29</sup>, G. de Wasseige<sup>4</sup>, J. Wilms<sup>54</sup>, R. Wojaczyński<sup>48</sup>, E. de Wolf<sup>15,27</sup>, T. Yousfi<sup>23</sup>, S. Zavatarelli<sup>11</sup>, A. Zegarelli<sup>30,8</sup>, D. Zito<sup>20</sup>, J. D. Zornoza<sup>5</sup>, J. Zúñiga<sup>5</sup>, N. Zywuca<sup>21</sup>.

<sup>1</sup>Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France.

<sup>2</sup>INFN, Sezione di Catania, Via Santa Sofia 64, Catania, 95123 Italy.

<sup>3</sup>Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France.

<sup>4</sup>Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France.

<sup>5</sup>IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València), c/Catedrático José Beltrán, 2, 46980 Paterna, Valencia, Spain.

<sup>6</sup>INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy.

<sup>7</sup>Università di Napoli "Federico II", Dip. Scienze Fisiche "E. Pancini", Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy.

<sup>8</sup>INFN, Sezione di Roma, Piazzale Aldo Moro 2, Roma, 00185 Italy.

<sup>9</sup>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.

<sup>10</sup>NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attikis, Athens, 15310 Greece.

<sup>11</sup>INFN, Sezione di Genova, Via Dodecaneso 33, Genova, 16146 Italy.

<sup>12</sup>University of Granada, Dept. of Computer Architecture and Technology/CITIC, 18071 Granada, Spain.

<sup>13</sup>Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Straße 1, 91058 Erlangen, Germany.

<sup>14</sup>Universitat Politècnica de València, Instituto de Investigación para la Gestión Integrada de las Zonas Costeras, C/Paranimf, 1, Gandia, 46730 Spain.

<sup>15</sup>Nikhef, National Institute for Subatomic Physics, PO Box 41882, Amsterdam, 1009 DB Netherlands.

<sup>16</sup>University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco.

<sup>17</sup>INFN, Sezione di Bologna, v.le C. Bertini-Pichat, 6/2, Bologna, 40127 Italy.

<sup>1</sup>also at Dipartimento di Fisica, INFN Sezione di Padova and Università di Padova, I-35131, Padova, Italy



- <sup>18</sup>Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy.
- <sup>19</sup>KVI-CART University of Groningen, Groningen, the Netherlands.
- <sup>20</sup>INFN, Laboratori Nazionali del Sud, Via S. Sofia 62, Catania, 95123 Italy.
- <sup>21</sup>North-West University, Centre for Space Research, Private Bag X6001, Potchefstroom, 2520 South Africa.
- <sup>22</sup>Instituto Español de Oceanografía, Unidad Mixta IEO-UPV, C/ Paranimf, 1, Gandia, 46730 Spain.
- <sup>23</sup>University Mohammed I, Faculty of Sciences, BV Mohammed VI, B.P. 717, R.P. 60000 Oujda, Morocco.
- <sup>24</sup>Subatech, IMT Atlantique, IN2P3-CNRS, Université de Nantes, 4 rue Alfred Kastler - La Chantreterie, Nantes, BP 20722 44307 France.
- <sup>25</sup>Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Matematica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy.
- <sup>26</sup>ISS, Atomistilor 409, Măgurele, RO-077125 Romania.
- <sup>27</sup>University of Amsterdam, Institute of Physics/IHEF, PO Box 94216, Amsterdam, 1090 GE Netherlands.
- <sup>28</sup>TNO, Technical Sciences, PO Box 155, Delft, 2600 AD Netherlands.
- <sup>29</sup>Università degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Matematica e Fisica, viale Lincoln 5, Caserta, 81100 Italy.
- <sup>30</sup>Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy.
- <sup>31</sup>Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "Guglielmo Marconi", Via dell'Università 50, Cesena, 47521 Italia.
- <sup>32</sup>Cadi Ayyad University, Physics Department, Faculty of Science Semlalia, Av. My Abdellah, P.O.B. 2390, Marrakech, 40000 Morocco.
- <sup>33</sup>University of the Witwatersrand, School of Physics, Private Bag 3, Johannesburg, Wits 2050 South Africa.
- <sup>34</sup>Università di Catania, Dipartimento di Fisica e Astronomia "Ettore Majorana", Via Santa Sofia 64, Catania, 95123 Italy.
- <sup>35</sup>INFN, LNF, Via Enrico Fermi, 40, Frascati, 00044 Italy.
- <sup>36</sup>INFN, Sezione di Bari, via Orabona, 4, Bari, 70125 Italy.
- <sup>37</sup>International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia.
- <sup>38</sup>University of Bari, Via Amendola 173, Bari, 70126 Italy.
- <sup>39</sup>University Würzburg, Emil-Fischer-Straße 31, Würzburg, 97074 Germany.
- <sup>40</sup>Western Sydney University, School of Computing, Engineering and Mathematics, Locked Bag 1797, Penrith, NSW 2751 Australia.
- <sup>41</sup>Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy.
- <sup>42</sup>Università di Genova, Via Dodecaneso 33, Genova, 16146 Italy.
- <sup>43</sup>Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, LPCCAEN, 6 boulevard Maréchal Juin, Caen, 14050 France.
- <sup>44</sup>University of Granada, Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., 18071 Granada, Spain.
- <sup>45</sup>NIOZ (Royal Netherlands Institute for Sea Research), PO Box 59, Den Burg, Texel, 1790 AB, the Netherlands.
- <sup>46</sup>Tbilisi State University, Department of Physics, 3, Chavchavadze Ave., Tbilisi, 0179 Georgia.
- <sup>47</sup>Leiden University, Leiden Institute of Physics, PO Box 9504, Leiden, 2300 RA Netherlands.
- <sup>48</sup>National Centre for Nuclear Research, 02-093 Warsaw, Poland.
- <sup>49</sup>Institut Universitaire de France, 1 rue Descartes, Paris, 75005 France.
- <sup>50</sup>University of Johannesburg, Department Physics, PO Box 524, Auckland Park, 2006 South Africa.
- <sup>51</sup>Eberhard Karls Universität Tübingen, Institut für Astronomie und Astrophysik, Sand 1, Tübingen, 72076 Germany.
- <sup>52</sup>Università di Pisa, Dipartimento di Fisica, Largo Bruno Pontecorvo 3, Pisa, 56127 Italy.
- <sup>53</sup>Laboratoire Univers et Particules de Montpellier, Place Eugène Bataillon - CC 72, Montpellier Cédex 05, 34095 France.
- <sup>54</sup>Friedrich-Alexander-Universität Erlangen-Nürnberg, Remeis Sternwarte, Sternwartstraße 7, 96049 Bamberg, Germany.
- <sup>55</sup>Université de Haute Alsace, 68100 Mulhouse Cedex, France.
- <sup>56</sup>University of Münster, Institut für Kernphysik, Wilhelm-Klemm-Str. 9, Münster, 48149 Germany.
- <sup>57</sup>Utrecht University, Department of Physics and Astronomy, PO Box 80000, Utrecht, 3508 TA Netherlands.
- <sup>58</sup>INFN, CNAF, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy.