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# Measurement of the depth dependence of coincidence rates induced by atmospheric muons with the first two KM3NeT Detection Units

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A measurement of the depth dependence of the coincidence rates induced by atmospheric muons was performed using the first two KM3NeT Detection Units.
The Detection Units are positioned at a depth of approximately 3.5 km. Even though the large water overburden shields them from the bulk of the cosmic ray air shower particles, a significant amount of downgoing atmospheric muons reaches the detector. Due to the considerable height of the strings (approximately 630 m from the lowest to the highest module) the muon flux is expected to change along the strings.
For this analysis every Digital Optical Module is considered as a stand-alone unit. The KM3NeT multi-PMT design allows each optical module to be calibrated in-situ and allows to identify atmospheric muon events by requiring high-multiplicity local coincidences.
The excellent agreement between the data and the Monte Carlo simulations confirms that the measured coincidence rate as a function of the depth matches the expected behaviour due to the depth dependence of the atmospheric muon flux.

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## 1. Introduction

KM3NeT is a neutrino research infrastructure under construction in the Mediterranean Sea. It aims to measure both high-energy neutrinos ("KM3NeT/ARCA") to identify cosmic high-energy neutrino sources, and low-energy atmospheric neutrinos ("KM3NeT/ORCA") to determine fundamental neutrino parameters, most importantly the neutrino mass ordering. The acronyms stand for "Astroparticle/Oscillation Research with Cosmics in the Abyss".

Both detectors consist of Digital Optical Modules (DOMs): pressure-resistant glass spheres each housing 31 3-inch photomultiplier tubes (PMTs) to detect Cherenkov light from charged particles. The DOMs are mounted on vertical lines called Detection Units (DUs) or "strings" in groups of 18. The nominal vertical spacing between DOMs is 36 m in the ARCA layout, while ORCA strings will have a smaller vertical separation optimized for low-energy neutrino interactions. More information about KM3NeT technology can be found in [1, 2, 3].

The first two fully functional ARCA DUs were deployed December 2015 (ARCA-DU1) and May 2016 (ARCA-DU2) at the Italian KM3NeT site at Capo Passero, Sicily. Although the current layout is very small compared to the envisioned two building blocks (of 115 DUs each) of KM3NeT phase 2.0 it is already sufficient to study the physics signal from atmospheric muons. Earlier, two KM3NeT prototypes called the Pre-Production Models (PPMs) were deployed, tested, and recovered: the PPM-DOM [4], a single DOM deployed at the site of the ANTARES experiment in April 2013, and the PPM-DU, a short KM3NeT string of only three DOMs, deployed at Capo Passero in May 2014 [5].

In this contribution a study of the depth dependence of the atmospheric muon-induced rates in the first two ARCA DUs is presented. Due to energy loss in the sea water the atmospheric muon flux is expected to decrease significantly along the approximately 630 m from the top DOM (floor 18) to the bottom DOM (floor 1) of a string. An analogous measurement of the atmospheric muon flux was published by ANTARES in [6]. However, the KM3NeT multi-PMT technology allows for a more robust analysis. Note that a similar depth dependence study was not possible with the PPM-DU because it did not span a sufficient depth range.

## 2. Method

In the sea water, the main optical background seen by the PMTs is a constant, depth-independent pulse rate from the radioactive decay of the naturally occuring isotope $^{40}$K. As shown in [4, 5] this background can be filtered out by utilizing the multi-PMT design.

The depth dependence analysis is based on *local coincidences*: clusters of two or more hits on the same DOM within a time window of 25 ns. The *multiplicity* of such a cluster is defined as the number of hit PMTs. The highest possible multiplicity is thus 31. The term "$m$-fold coincidence" will be used interchangeably with "local coincidence cluster of multiplicity $m$".

Three levels of hits are distinguished in KM3NeT. At the most basic level there are L0 hits which simply correspond to every occasion where a PMT pulse exceeds the threshold level. The time at which the threshold is crossed and the time spent over threshold by the pulse are sent to shore for all L0 hits. L1 hits have to fulfill the additional requirement of being part of a local coincidence. L2 hits, finally, are part of a hit pattern that causes one of the event triggers to fire. Different types of hits/data are useful for different analyses.

For this analysis, L1 hits are used. This analysis is therefore independent of the trigger settings, the reconstruction algorithms, the exact DOM positions, and the relative DOM time offsets. It only depends on the relative time offsets between PMTs in the same DOM ("intra-DOM timing") and the PMT efficiencies, both of which have been determined from the $^{40}$K calibration [3].

## 3. Monte Carlo (MC) simulations

The $\geq$2-fold background coincidence rates from $^{40}$K were simulated using OMGsim [3, 7], a Geant4-based simulation of the DOM. The rate of uncorrelated hits ("singles rate") was determined from data and analytically added to the $^{40}$K background rates.

Atmospheric muon events were generated with MUPAGE [8], a fast muon generator for neutrino telescopes based on parametric formulas. The parametric formulas are based on full air-shower simulations and experimental results. The subsequent generation and propagation of light and the response of the detector were simulated using the KM3NeT software packages KM3 [9] and JPP.

### Muon characteristics

MUPAGE simulates both single-muon events and multi-muon events ("muon bundles"). In the production generated for this analysis 13% of the simulated events contain more than one muon.

Muon tracks within a bundle are parallel and typically very close together. The median distance between the leading muon track and the farthest other muon track in the bundle is about 8 m, making it plausible that Cherenkov light from more than one muon track in the bundle is observed by the same DOM.

Figure 1 compares the contribution of single-muon and multi-muon MC events to local coincidences on DOMs of the two DUs as a function of the multiplicity. The relative contribution of muon bundles increases with the multiplicity. Above $m = 16$ coincidences are more likely to be caused by a muon bundle than by a single muon. However, even at high multiplicities the single-muon contribution is remains significant.

For single-muon MC events a high-multiplicity coincidence requires that the muon track passes very close to the DOM. As shown in Figure 2 the median distance of closest approach of single atmospheric muon tracks inducing $\geq$8-fold coincidences is 6 m or less, while more than 90% of such tracks pass the DOM within 20 m.

The energy of single-muon MC events is also seen to increase as a function of the multiplicity. As shown in Figure 3 the median energy of atmospheric muon tracks inducing a local coincidence increases rapidly from about 300 GeV at $m = 12$ to about 700 GeV at $m = 20$. A possible explanation for this is that at energies approaching 1 TeV the muon starts to lose a significant amount of energy in the form of discrete electromagnetic showers along the track. When such a shower occurs near a DOM it may partly envelop it. For lower multiplicities ($8 \leq m \leq 12$) the median atmospheric muon energy is about 300 GeV. Based on the steep atmospheric muon energy spectrum at sea level one might intuitively expect the atmospheric muon contribution to have been instead concentrated around energies of the order of a few tens of GeVs. However, the energy spectrum is effectively flattened at these depths due to the energy loss of the muons.

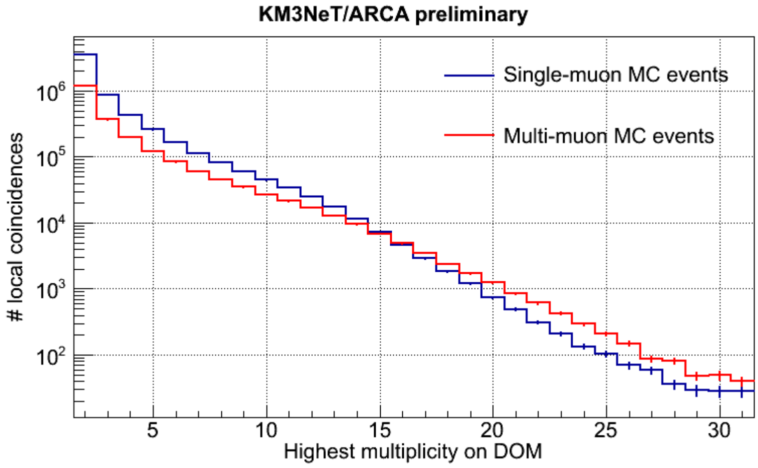


**Figure 1:** Distribution of the highest multiplicity induced on each DOM in atmospheric muon MC events. There is one entry per DOM with highest multiplicity $\geq 2$ per simulated event. The contributions from single-muon and multi-muon MC events are shown separately.

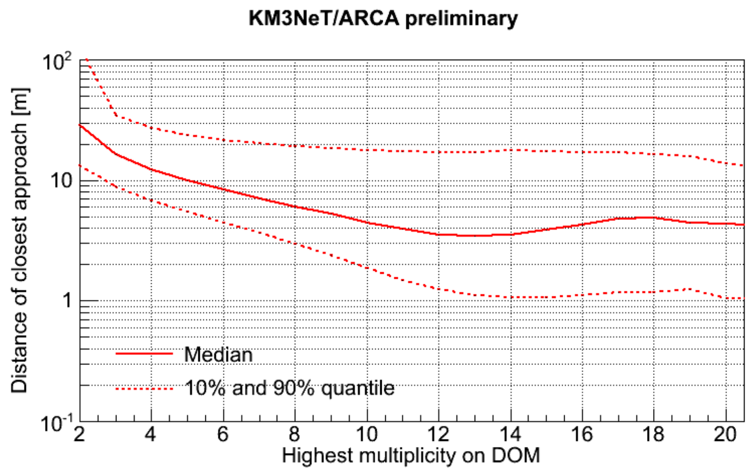


**Figure 2:** Distance of closest approach to a DOM as a function of the multiplicity in single-muon MUPAGE MC events. Muon tracks for which the expected track length does not reach up to the point of closest approach tot the DOM are ignored. If more than one coincidence occurs on the DOM in the event only the highest-multiplicity cluster is counted.

## 4. Data selection

For this analysis L1 data taken from December 23 2016 to January 13 2017 were used, with a total effective live time of 19.5 days.

The data are stored in "frames", each containing the L1 hits on a given DOM within a 0.1 s time period. A header containing information about the data taking conditions is included in

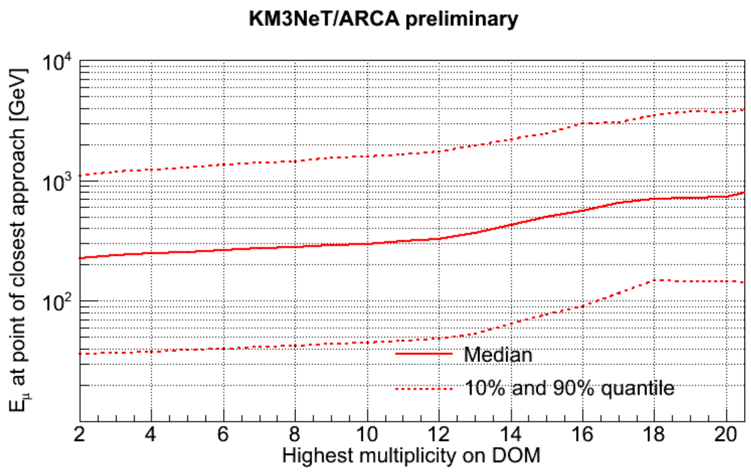


**Figure 3:** Expected muon energy at the point of closest approach to a DOM as a function of the multiplicity in single-muon MUPAGE MC events. If more than one coincidence occurs on the DOM in the event only the highest-multiplicity cluster is counted.

every frame. The header contains the average L0 rate of each PMT and a number of status flags indicating (among other things) whether the high rate veto (HRV) was activated. The HRV is a safety mechanism to protect the DAQ system from having to process too many hits at the same time. It is activated on a per PMT basis when the number of L0 hits on the PMT in a frame exceeds 2000, i.e. the frame-averaged PMT rate exceeds 20 kHz. Subsequent hits are then no longer processed for the duration of the frame.

To ensure a high-quality data sample, some selection criteria were applied at the frame level. The most stringent requirement was that the HRV should not be activated for any of the 31 PMTs. This results in the rejection of only 1% of the frames. Other selection criteria are applied but found to reject a negligible fraction of frames of order 0.01% or less.

Note that one DOM on ARCA-DU1 (floor 18) and three DOMs on ARCA-DU2 (floors 2, 11 and 12) were not functional during the selected data taking period.

The coincidence rates as a function of the multiplicity $m$ are shown in figure 4. A clear difference in slope is observed between the $^{40}$K-dominated background region at low multiplicities ($m < 7$) and the atmospheric muon-dominated region at high multiplicities. We conclude that when applying a cut of $m \geq 8$ the selected coincidences will be dominated by the atmospheric muon signal along the entire length of the DUs.

## 5. Results

Figure 5 shows the rate of $\geq$8-fold coincidences as a function of depth. The red dashed line is obtained with a MC simulation of a detector with identical PMTs. However, large deviations from this ideal detector behaviour are observed in data.

In order to correct the data for the different PMT responses the *PMT efficiencies* determined using the $^{40}$K in-situ calibration [3] were taken into account. The *PMT efficiency* is a single number assigned to each PMT to quantify how well it performs in-situ compared to the PMT model imple-

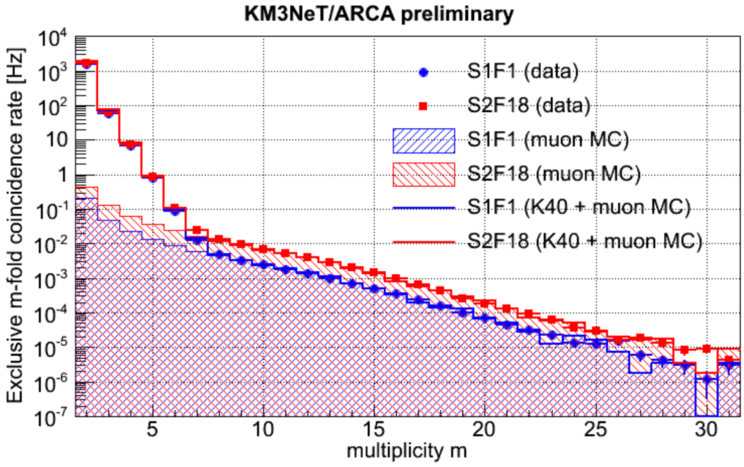


**Figure 4:** Coincidence rate as a function of the multiplicity. Two DOMs are shown: floor 1 (the lowest floor) of ARCA-DU1 and floor 18 (the highest floor) of ARCA-DU2. The data are overlayed with the expectations from MC simulations of $^{40}$K and atmospheric muons. Note that the PMT efficiencies in the $^{40}$K simulation have been varied within the systematic uncertainties in order to match the slope observed in data.

mented in the MC. A full atmospheric muon MC incorporating these measured PMT efficiencies was produced and compared to the ideal MC with uniform PMT efficiencies. For each DOM the ratio of the rates observed in these two MC's was then used to correct the data for the MC-simulated effect of the measured PMT efficiencies. These corrected data points are shown in figure 5 along with the uncorrected data. The corrected data points follow the expected ideal behaviour more closely, showing that the in-situ calibration improves data/MC agreement.

## 6. Conclusions and outlook

The expected depth dependence of the high-multiplicity coincidence rates due to the decrease of the atmospheric muon flux along the first two KM3NeT DUs has been measured. This result shows that the $\geq$8-fold coincidence rates decrease by roughly a factor 2 along the approximately 630 m depth difference between the top and bottom DOMs.

The data have been compared to MC simulations and an excellent agreement is reached. In the atmospheric muon MC simulation the signal ($\geq$8-fold coincidence rate) is mostly induced by atmospheric muons with a median energy of 300-400 GeV passing very close to the relevant DOM. In the simulation the largest contribution to the signal comes from single-muon events, although the contribution of muon bundles is non-negligible and even becomes dominant at high multiplicities.

It has been demonstrated for the first time that the PMT efficiencies determined from the $^{40}$K in-situ calibration significantly improve data/MC agreement. A follow-up of this investigation is foreseen where different atmospheric muon generators are compared, detector and MC systematics are thoroughly investigated, and the result is translated into a measurement of the physical atmospheric muon flux.

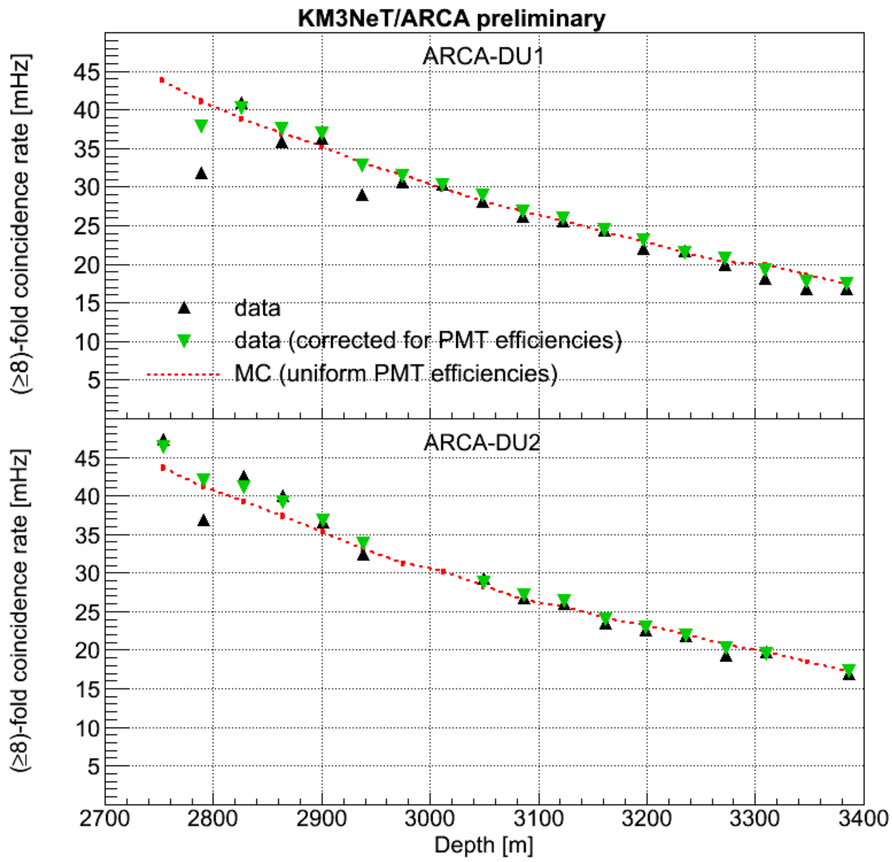


**Figure 5:** ≥8-fold coincidence rate as a function of the depth below the sea surface. The red dashed line shows the base expectation from an ideal MC with uniform PMT efficiencies which neglects the differences between individual PMTs as determined from in-situ calibration. The black points show the uncorrected data. The green points show the data corrected for the effect of the PMT efficiencies. Statistical errors bars are included but are too small to be visible over the markers.

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