PROCEEDINGS OF SCIENCE

Measurement of optical water properties using stopping muons in KM3NeT/ORCA

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The KM3NeT Collaboration is currently building two neutrino detectors in the Mediterranean Sea. The KM3NeT/ARCA telescope is located off-shore Sicily, Italy, at a depth of about 3.5 km, designed to study cosmic neutrinos. KM3NeT/ORCA is being built off-shore Toulon, France, at a depth of about 2.5 km, with the main physics objective being the determination of the neutrino mass ordering and the precise measurement of oscillation parameters. Optical water properties and light detection efficiency are among the main systematic uncertainties for these objectives. In this work, reconstructed atmospheric muons stopping within KM3NeT/ORCA are studied in order to constrain these uncertainties. Such muons lose energy predominantly through ionisation, which makes them an eligible light source for this study. The improved constraints on these uncertainties will result in better sensitivities in neutrino oscillation studies.

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1. Introduction

The KM3NeT Collaboration operates two neutrino detectors at the bottom of the Mediterranean Sea [1]. The KM3NeT/ARCA telescope is off-shore Sicily, Italy, at a depth of about 3.5 km, while the KM3NeT/ORCA detector is off-shore Toulon, France, at about 2.5 km depth. The detectors are modular arrays of Digital Optical Modules (DOMs) [2], each housing 31 PhotoMultiplier Tubes (PMTs) and arranged on vertical lines. Each line contains 18 DOMs. While still under construction, both detectors are taking data with 33 and 28 lines installed at the KM3NeT/ARCA and KM3NeT/ORCA sites, respectively. The analysis presented in this work is performed with the KM3NeT/ORCA detector in a 6-line configuration, hereafter referred to as ORCA6.

A primary source of systematic uncertainty in KM3NeT arises from the optical properties of water - the absorption and scattering lengths - and the light detection efficiency. These uncertainties impact the neutrino energy estimation, which is crucial for high-energy neutrino astronomy with KM3NeT/ARCA [3] and for determining the neutrino mass ordering with KM3NeT/ORCA [4]. Currently, uncertainties on the light absorption length and the detection efficiency are independently estimated at $\pm 10\%$ [3].

This work is devoted to the in-situ measurement of water optical properties and light detection efficiency at the KM3NeT/ORCA site. The measurement is performed by exploring the light produced by down-going atmospheric muons that stop within the ORCA6 detector. The vast majority of such muons have energies below 100 GeV when entering the sensitive volume of the telescope, where they lose energy predominantly through ionisation. They can thus be considered as minimum ionising particles [5], with minimal stochastic energy losses, and a well-defined light emission profile. This makes stopping muons a reliable source of light for the study of light propagation and detection in water.

The methodology for identifying stopping muons has been previously developed for ORCA6 [6]. For this measurement, a selection approach referred to as *Selection with simple cuts* in [6] has been adapted. In order to increase the purity of the stopping muon data sample, a cut on the cosine of the reconstructed zenith angle, $\cos\theta$, is modified to select more vertical muons, $\cos\theta < -0.85$ ($\cos\theta = -1$ indicates vertically down-going). Additionally, a cut on the parameter defining the accuracy of the direction reconstruction is added, resulting in an increase of the purity of the stopping muon selection to 97%.

2. Probability density functions

In KM3NeT, Cherenkov light from highly-relativistic charged particles is detected by an array of PMTs. Whenever the PMT signal pulse read-out exceeds a predefined threshold, a “hit" is recorded, comprising the starting time of the signal, its duration, and PMT identification number.

In this work, the Probability Density Functions (PDFs) of light detection are obtained using hits from selected stopping muons. These PDFs are calculated as one-dimensional histograms where the dimension is the distance of closest approach between the muon track and each PMT, R, given the reconstructed track direction and position. The accuracy of the stopping muon direction reconstruction is about 0.8°, and the stopping point resolution is about 4 m [6]. The PDFs are calculated as the number of detected hits divided by the number of PMTs capable of detecting hit(s)

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in each histogram bin. PMTs that are not active at the time of the muon event are excluded from the calculation.

An example of the PDF calculation using muon tracks simulated and reconstructed in ORCA6 is presented in Fig. 1. The top plot shows the number of detected hits and the number of hits that could have been possibly detected as a function of the distance of closest approach. Their ratio, the PDF, is shown in the bottom plot. As can be seen, the PDF does not change significantly for distances above 60 m since this region becomes dominated by background light from the ^{40}K β-decays, bioluminescence, and other radioactive decays of nuclei in the DOM glass and water. The subsequent analysis focuses on PDFs obtained for distances below 60 m.

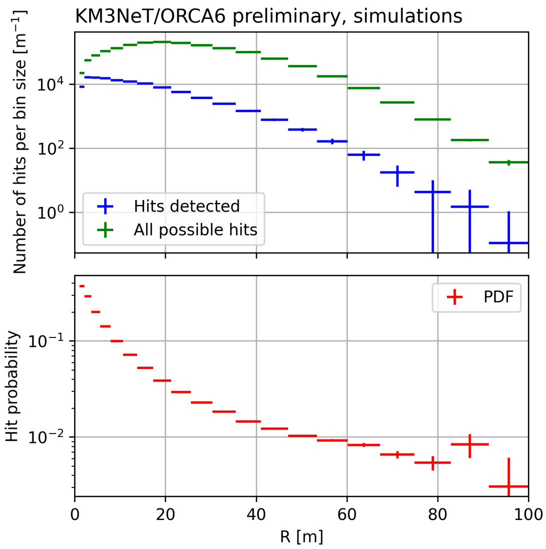

Figure 1: Top: Number of detected hits (blue) and the number of hits that could have been possibly detected (green) as a function of the distance of closest approach. Bottom: the probability of a hit detection. Horizontal lines indicate the half bin size, statistical errors are shown with vertical lines.

3. Stopping muon generator

The measurement of water optical properties in this work is performed by comparing the PDF obtained from the data to the PDFs obtained from simulated Monte Carlo (MC) samples assuming different absorption and scattering lengths. Given the high purity of the stopping muon selection (97%), the efficiency of the selection is only 2%. Therefore, acquiring sufficient statistics of selected stopping muons in each of the generated MC samples is CPU-time consuming. To address this issue, a dedicated stopping muon generator was developed. The generation is performed in 3 steps:

1. A random point and direction are generated inside the sensitive volume of the detector.
2. The intersection point between the line formed by the point and direction of step 1 and a plane 300 m above the upper part of the detector is calculated. This defines the starting point of the muon.

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3. The initial muon energy is calculated using the distance between the starting point and the point determined in the first step. In this way, the muon is expected to stop inside the detector's sensitive volume. The calculated energy is added with an energy value randomly picked in the [-75 GeV, 75 GeV] interval to take into account possible wrongly selected stopping muons.

Subsequent muon propagation, light generation, and track reconstruction are performed using the internal KM3NeT software.

4. Systematic uncertainties

4.1 Dependence on the muon flux

In order to estimate any possible bias introduced by the stopping muon generator, a study of the dependence of the PDFs on the atmospheric muon flux was performed. PDFs from three different MC samples were compared: those from the stopping muon generator, MUPAGE [7, 8], and the stopping muon generator with a high-energy flux component added, proportional to $E^{-1.5}$ (E is muon energy). MUPAGE is the MC generator for muon bundles used in KM3NeT for the atmospheric muon simulations. Since MUPAGE incorporates the simulation of multiple muons in the bundles, the corresponding PDF dependence is taken into account. The inclusion of the $E^{-1.5}$ spectrum helps in checking the dependence of the flux while artificially enhanced with high-energy muons. The left plot in Fig. 2 shows the initial muon energies in the three cases mentioned above. The spectra are normalised such that each is equal to 1 at 100 GeV.

The PDFs for the three aforementioned muon samples are displayed on the right plot of Fig. 2. The PDFs are compared using the ratios and the pull plot with respect to the MUPAGE PDF. The PDFs differ by less than 3% and agree within the 3σ band. In the following, a systematic uncertainty of 3% is used to account for the combined dependence on flux and multi-muon bundles.

4.2 Simulation of light

The simulation of light generation, propagation, and detection in KM3NeT is performed with two alternative software packages, JSirene [9] and KM3Sim [10]. JSirene is a program that evaluates the number of photoelectrons recorded by a PMT, exploiting the tabulated probability density functions of the photon arrival times. KM3Sim is a GEANT4-based [11] application for a full simulation of optical Cherenkov photons from charged particles. Since KM3Sim performs the detailed tracking of individual particles, it is CPU-time demanding, making JSirene a faster alternative for the simulation of atmospheric muons in KM3NeT. In this work, the differences between the PDFs calculated using either JSirene or KM3Sim are treated as systematic uncertainties. The comparison of the PDFs from the two light generators is shown in the left plot of Fig. 3. The differences between the PDFs are added to the Test Statistics (TS) calculation as described in Sec. 5.1.

4.3 Scattering length

In the current approach, the sensitivity is insufficient for a precise measurement of the scattering length, L_{sct}. Thus, the possible mis-modelling of the scattering length is treated as a systematic

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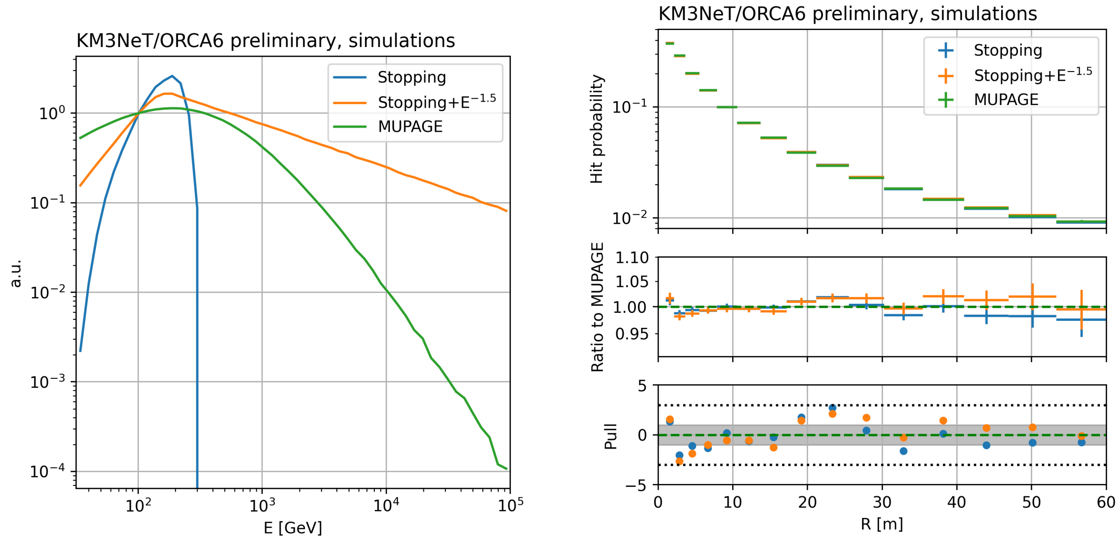

Figure 2: Left: the muon energy spectra for three MC samples used for the flux dependence study: energy calculated using stopping muon generator (blue), energy calculated in the same way, summed with the flux proportional to $E^{-1.5}$ (orange), and the MUPAGE energy spectrum (green). Right: comparison of the PDFs in terms of ratio to the MUPAGE PDF and the pull with respect to it. Horizontal lines indicate the half bin size, statistical errors are shown with vertical lines. The grey band on the pull plot indicates the differences within the 1σ interval. The dotted lines on the bottom plot indicate the 3σ difference.

uncertainty. For this purpose, the two MC samples were generated both with nominal absorption length, but with the scattering length scaled by 0.9 and 1.1, respectively, relative to the nominal value, L_{sct}^{nom}. The comparison of the PDFs calculated using these two samples with modified scattering lengths is shown in Fig. 3, right plot. The differences observed are treated as systematic uncertainties in the same way as for the differences arising from the two light generators.

5. Results

5.1 Sensitivity estimation

In order to estimate the sensitivity of PDFs to changes in the absorption length, L_{abs}, several MC samples were produced using the stopping muon generator with the absorption length scaled. The absorption length was scaled from 0.9 to 1.1 of the nominal value, L_{abs}^{nom}, with a step of 0.02, at each light wavelength (300–710 nm).

The modified PDFs are also scaled to account for uncertainties in the overall light yield and light detection efficiency. Such scaling is referred to as *normalisation* (N) in the following. The normalisation scaling is performed from 0.9 to 1.1 of the nominal value, N^{nom}, with a step of 0.01.

Test Statistic (TS) values are calculated for each modified MC PDF and compared against the MUPAGE PDF with nominal absorption and normalisation to estimate the sensitivity of the approach. The TS is defined as

$$\mathrm{TS}(L_{abs}, N) = \sum_{i=1}^{N_{\mathrm{bins}}} \{ \frac{[n_{obs}^i - (n_{exp}^i(L_{abs}, N) + c_1 \cdot \sigma_{\mathrm{light}}^i + c_2 \cdot \sigma_{sct}^i)]^2}{(\sigma_{obs}^i)^2 + (\sigma_{exp}^i(L_{abs}, N))^2} \} + c_1^2 + c_2^2. \qquad (1)$$

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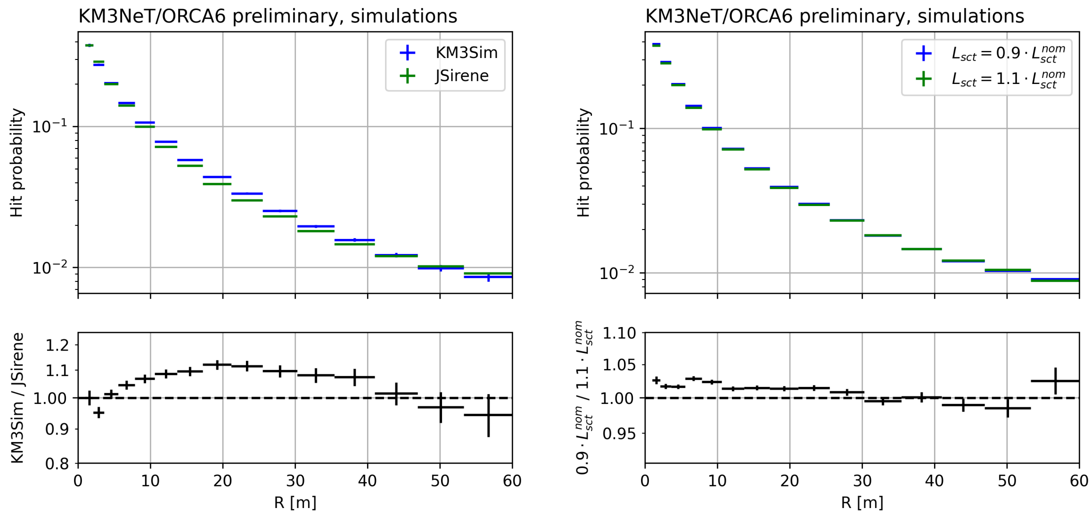

Figure 3: Top left: PDFs resulting from MC samples where JSirene (green) and KM3Sim (blue) are used as the light generators. Top right: PDFs calculated assuming the scattering length scaled by 1.1 (green), 0.9 (blue) of the nominal value. Bottom: ratio between the PDFs. Horizontal lines indicate the half bin size, statistical errors are shown with vertical lines.

Here, n^i_{obs} and σ^i_{obs} are the MUPAGE PDF value and its statistical error in the i-th bin, with the total number of bins being N_{bins}. The $n_{exp}(L_{abs}, N)$ value is the MC PDF with modified absorption length and normalisation. The term $\sigma_{exp}(L_{abs}, N)$ incorporates the statistical uncertainty and the 3% systematic uncertainty due to the flux dependence, summed in quadrature. The term σ^i_{light} accounts for the differences between the PDFs obtained with KM3Sim and JSirene and is defined as $\sigma^i_{\text{light}} = n^i_{\text{KM3Sim}}(L^{nom}_{abs}, N^{nom}) - n^i_{\text{JSirene}}(L^{nom}_{abs}, N^{nom})$. The systematic uncertainty due to scattering is $\sigma^i_{sct} = [n^i_{\text{JSirene}}(L_{sct} = 1.1 \cdot L^{nom}_{sct}) - n^i_{\text{JSirene}}(L_{sct} = 0.9 \cdot L^{nom}_{sct})]/2$. The c_1 and c_2 values are profiled for each modified L_{abs} and N by randomly sampling values from a Gaussian distribution with a mean of 0 and a width of 1.

The minimum TS value found at the best-fit point is subtracted from the TS values across the entire L_{abs}-N scan. The obtained values of the difference in TS follow a χ^2 distribution with 2 degrees of freedom. The 90% Confidence Level (CL) contour for this distribution is plotted in Fig. 4.

5.2 Measurement

The same TS as in Eq. 1 is used in order to obtain the CL contour for the comparison with the data. In this case, n^i_{obs} and σ^i_{obs} are the PDF value and its statistical error for the data. The livetime used in this work corresponds to 10 days of the ORCA6 data.

The minimum TS value from the comparison with the data is found for $L_{abs} = 0.96 \cdot L^{nom}_{abs}$ and $N = N^{nom}$. The 90% CL contour is given in Fig. 4. To ensure enclosed contours, three additional MC samples were produced for the comparison with the data, with L_{abs} scaled by 0.88, 1.12, and 1.14. As shown in the plot, the changes in L_{abs} and N are anti-correlated and the corresponding systematic uncertainties should be considered jointly. Fig. 5 shows the comparison of the data PDF

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with three different MC PDFs: the best-fit point, the nominal absorption length and normalisation, and a point outside the 90% CL contour ($L_{abs} = 0.94 \cdot L_{abs}^{nom}$ and $N = 0.96 \cdot N^{nom}$).

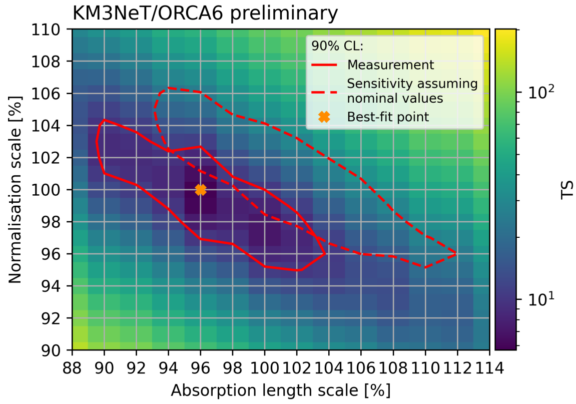

Figure 4: The TS values for the comparison of the data PDF with the MC PDFs with modified absorption length and normalisation. The solid contour indicates the 90% CL for the measurement. The best-fit point for the data is shown with the orange cross. The dashed contour shows the expected sensitivity estimated using MUPAGE with nominal values for the absorption length and normalisation.

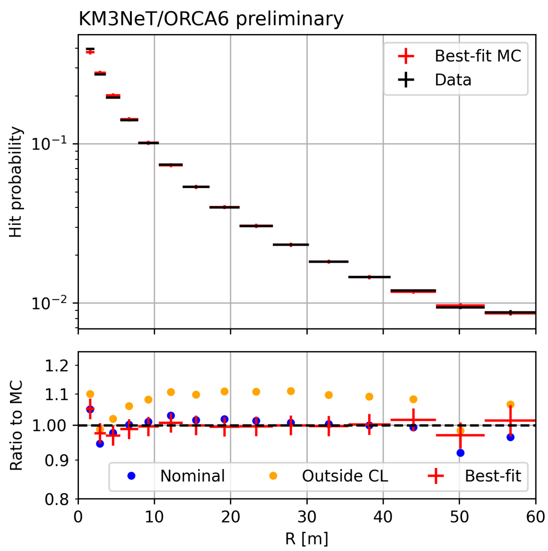

Figure 5: Top: comparison between the data PDF (black) and the best-fit MC PDF, $0.96 \cdot L_{abs}^{nom}$ and N^{nom} (red). Bottom: the ratio between the data PDF and the MC PDFs for the best-fit point, L_{abs}^{nom} and N^{nom} (blue), and the point outside the allowed 90% CL contour, $0.94 \cdot L_{abs}^{nom}$ and $0.96 \cdot N^{nom}$ (orange). The errors are shown only for the best-fit point for better visibility.

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6. Conclusions

In this work, a novel method to measure the light absorption length and the light detection efficiency using in-situ underwater data is reported. The method exploits the light from muons that stop within the sensitive volume of ORCA6. The sensitivity to the measurement stems from the high purity of the stopping muon selection and the accuracy of the direction and position reconstruction.

The best agreement between the ORCA6 data and the MC simulations is observed for an absorption length of 0.96 of the nominal value and for the nominal normalisation. The nominal water properties are within the allowed 90% CL contour. The measurement reported in this work allows for constraining the systematic uncertainties on the light absorption length and its detection efficiency at a level well below the current limits, with an uncorrelated uncertainty of ±10% on both parameters.

The methodology has potential for further development. For instance, the comparison of the data PDF to the MC PDFs in a delayed time window with respect to the arrival time of the direct Cherenkov light may increase the sensitivity to the scattering length. Furthermore, since the livetime used in this work corresponds to only 10 days of the ORCA6 data, our results indicate that the water optical properties can be monitored on a weekly basis with larger detectors.

References

[1] S. Adrián Martínez et al. (KM3NeT Collaboration), J. Phys. G: Nucl. Part. Phys. **43** 084001 (2016).

[2] S. Aiello et al. (KM3NeT Collaboration), JINST **17**, P07038 (2022).

[3] S. Aiello et al. (KM3NeT Collaboration), Nature **638**, 376–382 (2025).

[4] S. Aiello et al. (KM3NeT Collaboration), Eur. Phys. J. C **82**, 26 (2022).

[5] S. I. Klimushin, E. V. Bugaev, and I. A. Sokalski, PoS(ICRC2001).

[6] L. Bailly-Salins for the KM3NeT Collaboration, PoS(ICRC2023)203.

[7] Y. Becherini, A. Margiotta, M. Sioli, and M. Spurio, Astropart. Phys. **25**, 1 (2006).

[8] G. Carminati, A. Margiotta, and M. Spurio, Comput. Phys. Commun. **179**, 915 (2008).

[9] M. de Jong and E. van Campenhout, arXiv.2305.19626 (2023).

[10] A. G. Tsirigotis, A. Leisos, and S. E. Tzamarias, Nucl. Instrum. Methods Phys. Res. A **626-627**, 185–188 (2011).

[11] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Methods Phys. Res. A **506**, 250–303 (2003).

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