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5 Analysis of the first KM3NeT-ORCA data

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10 **ABSTRACT:** ORCA, Oscillation Research with Cosmics in the Abyss, is the low energy KM3NeT
11 neutrino underwater detector, located in the French Mediterranean sea. It comprises a dense
12 array of optical modules designed to detect the emitted Cherenkov light emitted from charged
13 particles resulting from neutrino interactions in the vicinity of the detector. Its main physics goal
14 is the determination of the neutrino mass hierarchy by quantifying the matter-induced effect on the
15 oscillation probabilities of atmospheric neutrinos in the energy range, 3-50 GeV, where the effects
16 of neutrino oscillation phenomena are dominant.

17 In 2019, four detection units were operational. Two more had been added in early 2020. This
18 work presents an overview of the detector performance in 2019 and 2020 as well as its sensitivity
19 to neutrino oscillations.

20 **KEYWORDS:** Cherenkov detectors, Neutrino detectors

21 **ARXIV EPRINT:** [1234.56789](https://arxiv.org/abs/1234.56789)

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27 1 Introduction

28 The KM3NeT Collaboration is building the 2 next-generation large volume neutrino detectors in
29 the Mediterranean Sea. Both telescopes rely on the same technology to detect the Cherenkov light
30 emitted by secondary particles after neutrino interaction. Digital Optical Modules (DOMs), made
31 of 31 PMTs pointing in every direction, are combined on a line to form a Detection Unit (DU).
32 The ARCA detector (Astroparticle Research with Cosmics in the Abyss) is located close to Sicily
33 (Italy) at 3.4 km depth and optimized for neutrinos of energies from 1 TeV to 1 PeV. To reach a km³
34 volume, it will be made of 230 DU sparsely separated. ORCA (Oscillation Research with Cosmics
35 in the Abyss) is the low energy counterpart, situated at 2.4 km depth on Toulon’s (France) shores.
36 It is optimized for neutrino energies between 1 GeV and 100 GeV, making it especially suited for
37 atmospheric neutrino detection. When completed, the 115 DU of the ORCA detector will achieve
38 a detection volume of about 7 Mton.

39 Atmospheric neutrinos are offering a great source to study neutrino oscillation. While covering
40 a large energy range, they also provide a large range of propagation distances, from tens of km to
41 ten of thousand km. Coupled with the large detection volume of a deep-sea cherenkov telescope,
42 ORCA aims to probe the atmospheric oscillation parameters Δm_{23}^2 and θ_{23} with world leading
43 sensitivity. The long path of neutrinos through the earth also offer an occasion to probe the neutrino
44 mass ordering [1].

45 Since mid-2019 4 DUs are steadily taking data in the ORCA detector. This initial detector was
46 raised to 6 DUs after a deployment campaign in January 2020. In this communication, the emphasis
47 will be put on the 4 DU configuration (ORCA4). More recent results with the 6 DUs configuration
48 are shown in [2].

49 2 Neutrino signal extraction

50 The total data taking period for ORCA4 is 191.9 days, with a detector uptime of about 91%.
51 However, for the study presented here, a significant part of the runs were discarded, based on the
52 fact that technical issues were encountered and no proper study was done to estimate the impact on

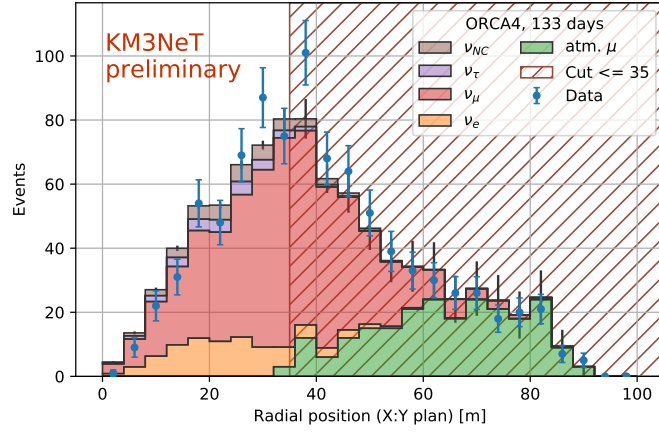


Figure 1. Reconstructed interaction point distance to detector center in horizontal plane. The muons (green) are produced in the atmosphere, therefore here the radial position correspond to the point where the light produced by the track start to be detected. It explains the very different behaviour compared to neutrinos, for which the starting point of the track can be close to the detection volume.

53 neutrino sensitivity. The problem were later solved, allowing for a larger run acceptance in the
 54 future study. After applying this run selection, the exposure time is 133.1 days.

55 During this period, the telescope was triggered with a typical rate of 6-7 Hz, while the averaged
 56 PMT rate was fluctuating between 7 kHz and 14 Hz, demonstrating the triggering algorithm robust-
 57 ness against random background. This rate is dominated by atmospheric muons events reaching
 58 the detector volume. Based on Monte-Carlo simulation, the trigger-rate from atmospheric muons
 59 is expected to be not less than 600000 events per day. Considering that in the same condition 40
 60 neutrinos are expected, it requires a 5 orders of magnitude background reduction.

61 The first criteria is applied on the zenith angle of the event. The selection focuses on the
 62 upgoing events, where no atmospheric muons are expected. However, a small fraction are miss-
 63 reconstructed as upgoing, which make the upgoing channel still dominated by this background.
 64 Secondly, by selecting tracks where the reconstruction algorithm yields a better quality estimation,
 65 a suppression of the atmospheric muon component is achieved, while also selecting neutrinos
 66 with the best angular and energy resolution. Finally, to get rid of the remaining contamination, a
 67 containment cut is defined. For ORCA4, the distance between the reconstructed interaction point
 68 (i.e. where the track start) and the detector center in the horizontal plane is computed. This radial
 69 position offers a good leverage to reject the remaining spurious muons events, as it can be seen on
 70 figure 1.

71 381 events are surviving the selection, which correspond to a daily event rate of $2.86 \pm$
 72 0.15 day^{-1} . For the same period, the Monte-Carlo simulations¹ are predicting $2.92 \pm 0.02 \text{ day}^{-1}$ ²
 73 for the neutrinos and $0.02 \pm 0.02 \text{ day}^{-1}$ for atmospheric muons, indicating a very good neutrino

¹Neutrinos events are generated using gSeaGen [7] neutrino generator and weighted using the HKKM2014 [5] flux at Frejus position. Oscillation are propagated using *nuFit 5.0* [3] best-fit values and earth PREM model [4]. Atmospheric muons are generated using MUPAGE [6].

²Uncertainties on Monte-Carlo are only considering stastiscal errors. Systematical uncertainty sources, such as the flux shape/normalisation, the interaction cross-section, have still to be included.

74 purity for the selected sample.

75 In addition to the rate agreement between data and Monte-Carlo simulations, figure 1 and
 76 figure 2 are showing respectively the good agreement in term of position in the detector and
 77 reconstructed energy/direction.

78 3 Neutrino oscillation sensitivity

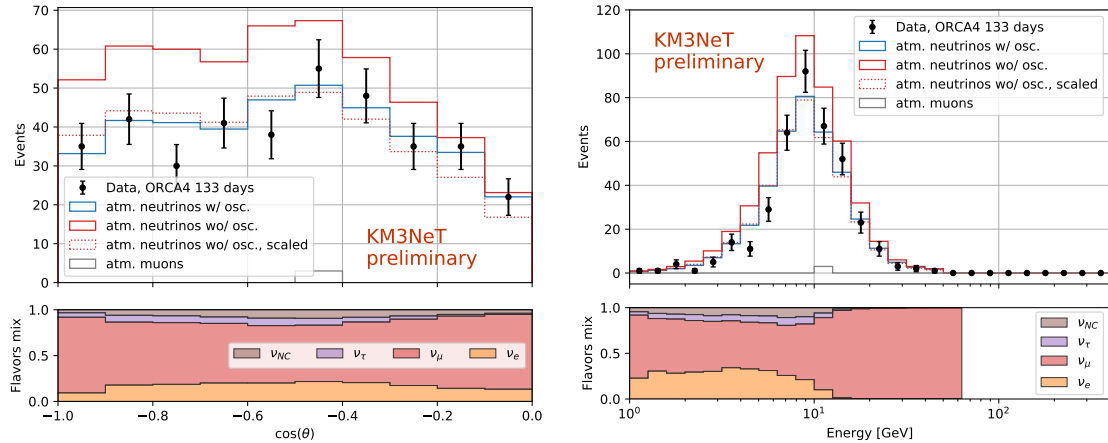


Figure 2. Left: $\cos(\text{zenith})$ angle distribution for selected events. Right: reconstructed energy for selected events, based on the reconstructed track length.

79 The zenith angle distribution on figure 2 gives a comparison of the expected results without and
 80 with oscillation, using best-fit value from *nuFit* 5.0[3]. The distribution shows an angle dependant
 81 effect of the oscillation, more pronounced for upgoing events (i.e. $\cos(\theta) = -1$), even if the effect
 82 is smeared by the degraded angular resolution of such a small detector.

83 The energy used in this study is based on the reconstructed track length, converted to energy
 84 using a constant ionization potential for the muons of $0.25 \text{ GeV} \cdot \text{m}^{-1}$, which is an acceptable
 85 approximation in the considered energy range (1-100 GeV). The distribution shown of figure 2 is
 86 clearly peaked around 10 GeV, which can be explained by the current detector geometry. Being a tall
 87 and thin cylinder, most of the tracks are crossing the detection volume for about 40 m, corresponding
 88 to 10 GeV reconstructed energy. Due to this limitation in the visible track length, the detector energy
 89 response is highly degraded for events above 10 GeV. This leads to a situation where the neutrino
 90 oscillation effect is limited to a amplitude modulation of the distribution, reducing the impact of the
 91 energy dependence of the oscillation effects in the detector sensitivity.

92 In order to properly extract the sensitivity to neutrino oscillation, the data are represented
 93 in term of L/E ratio, as it can be seen on figure 3. By comparing no-oscillation and oscillation
 94 hypothesis to the data with a free normalisation³, the selected events favoured neutrino oscillation
 95 at 2.5σ .

³The systematic uncertainties were still not thoroughly studied when this result was presented. By only fitting the shape, the collaboration is being very conservative.

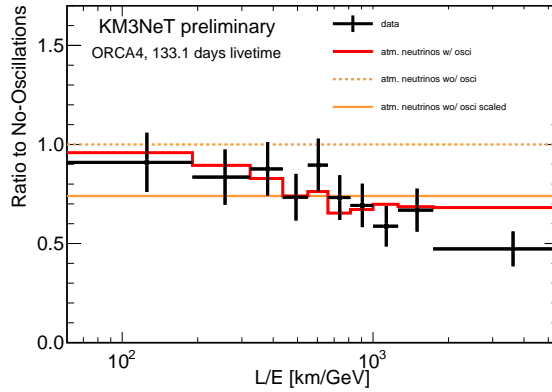


Figure 3. L/E distribution, normalized to the no-oscillation hypothesis. L is the propagation length of the neutrino, obtained from the zenith angle. E is the reconstructed energy.

96 4 Summary and discussion

97 The KM3NeT/ORCA detector is currently being deployed in the Mediterranean Sea. In this
 98 communication, we present an analysis of 133.1 days of data taken with the first 4 of the 115
 99 Detection Units to be deployed. Even with such a small fraction of the detector, a neutrino
 100 sample with a good purity can be extracted, with a rate of about 2.9 neutrinos per day. The
 101 agreement between data and Monte-Carlo simulation, for both the shape and the rate, shows a good
 102 understanding of the experimental apparatus response.

103 The selected data are favouring oscillation against no-oscillation at 2.5σ level, in a conservative
 104 comparison only including the shape of the L/E distribution. The detector is already close to probe
 105 neutrino oscillation, even with a very simple analysis that so far does not include events other than
 106 track-like events, i.e. mainly muons neutrinos, for which energy resolution is highly degraded by
 107 the detector geometry.

108 The 6 DU detector currently operated is offering a larger data sample, combined to better
 109 resolution from a larger detector, resulting in an improved sensitivity. In parallel, development
 110 effort are done to introduce a cascade event reconstruction, a separation between cascade and track
 111 events, as well as properly estimated systematic errors.

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