PROCEEDINGS OF SCIENCE

Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6

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The KM3NeT/ORCA detector (Oscillation Research with Cosmics in the Abyss) is an underwater array of Digital Optical Modules. These are spheres that host 31 photomultiplier tubes each, and they are tied together in vertical structures (the Detection Units-DUs) anchored on the seabed. This configuration allows the detection of neutrino events using the Cherenkov radiation emitted by secondary particles originating from neutrino interactions in the abyssal depths of the Mediterranean Sea. The KM3NeT/ORCA detector is being deployed at a depth of 2450 m, approximately 40 km South of Toulon, France with the determination of the Neutrino Mass Ordering being the main physics goal of the detector. In this work, we present a measurement of the atmospheric muon neutrino flux between 1 GeV and 100 GeV, using data collected with the 6-DU configuration of KM3NeT/ORCA (KM3NeT/ORCA6). The data analyzed corresponds to a time period of one and a half years. A high-purity atmospheric neutrino sample is selected using a Machine Learning classifier (Boosted Decision Tree). Subsequently, an unfolding scheme is used to obtain an estimation of the atmospheric muon neutrino energy spectrum. The impact of the systematic uncertainty sources in the measurement is also presented. This measurement illustrates the ability of the KM3NeT/ORCA detector to provide experimental information, even with an early-stage detector configuration, at an energy region in which only few measurements exist by other experiments.

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1. Introduction

Atmospheric neutrinos produced in cosmic ray interactions with nuclei in the atmosphere. However, the properties of the hadronic interactions which dominate the production of these neutrinos are only loosely constrained. The lower part of their energy spectrum is also suitable to study neutrino oscillations, and to test several extensions of the Standard Model. Finally, the study of neutrinos from astrophysical sources largely profits from constraining the atmospheric neutrino flux. Despite the plethora of research topics related with atmospheric neutrinos, there is limited experimental information on their flux below the energy of 100 GeV. A measurement of the atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux is presented in this work, using data collected with a preliminary KM3NeT/ORCA configuration.

2. The KM3NeT/ORCA detector

KM3NeT [1] is a research infrastructure aiming to study astrophysical sources as well as to perform particle physics studies, through the detection of neutrinos in the abyssal depths of the Mediterranean Sea. The KM3NeT/ORCA detector (Oscillation Research with Cosmics in the Abyss), currently under construction, is deployed at 2450 m depth South of Toulon, France. It consists of vertical structures called Detection Units (DUs), equipped with 18 spherical Digital Optical Modules (DOMs). Each DOM hosts a set of 31 photomultiplier tubes (PMTs). This array of PMTs is capable of detecting neutrino events from the Cherenkov radiation induced by the daughter particles of their interactions is seawater. Each Detection Unit is anchored to the seabed and remains vertical due to the buoyancy of the DOMs and of a buoy which is tied on its top. The distance between two consecutive DOMs in ORCA is ~ 9 m, and between the DUs is ~ 20 m. When completed, the ORCA detector will consist of 115 DUs, instrumenting a mass of almost 7 Mton. It is currently under operation with 24 DUs.

3. Atmospheric neutrino event selection

The data used in this analysis have been collected with the 6-DU configuration of the KM3NeT/ORCA detector, referred to as ORCA6, which was operating between January 2020 and November 2021. The selected data livetime is equal to 510 days, with an equivalent exposure of 433 kton·years. A run-by-run Monte Carlo simulation strategy has been followed, where each data-taking run is simulated separately, to account for the variation of the detector and data-taking conditions. Atmospheric muon and atmospheric neutrino CC and NC events are simulated. For the latter, weights are extracted using the HKKM14 conventional atmospheric neutrino flux [2], taking into account neutrino oscillations according to the parameters in NuFIT 5.2 [3].

The contribution of pure noise events, produced by ^{40}K decays in seawater, is suppressed by applying minimum requirements on the maximum likelihood and number of hits of the reconstruction algorithm (anti-noise criteria). To suppress the contribution from atmospheric muons, the Earth is used as an atmospheric muon filter, selecting events with an upward-going reconstructed direction.

The aforementioned criteria reduce the event selection procedure into a binary classification problem, the discrimination between atmospheric neutrinos and atmospheric muons reconstructed

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as upward-going events. *Event variables* were constructed and used as features in an adaptive Boosted Decision Tree classifier, implemented in TMVA [4]. These event variables are based on criteria related with signal-like and triggered hits, the quality of the event reconstruction, the event topology, and the deposited charge. A framework was also developed to optimize the BDT parameters such as the number of trees, max tree depth, and the value of the adaptive boosting parameter. The distribution of the BDT score for the reconstructed as upward-going events that meet the anti-noise criteria is shown in Fig. 1.

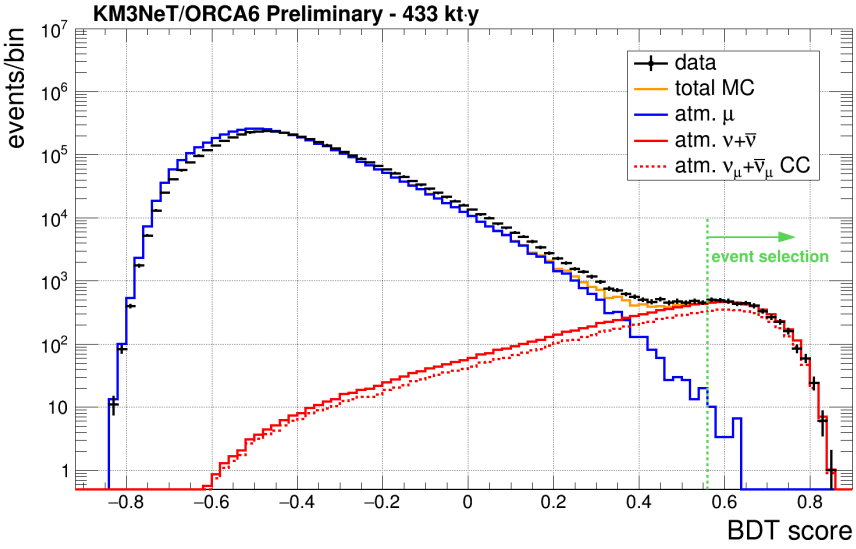

Figure 1: BDT score distributions for the upward-going ORCA6 events that survive the anti-noise criteria.

Events with a BDT score greater than 0.56 are chosen after an optimisation of the event selection. The number of data and MC simulated events are presented in Table 1. The chosen BDT score cut value yields a high signal efficiency for an -almost- complete suppression of the atmospheric muon background. Moreover, $\sim$ 75% of the MC simulated events that have been selected are $\nu_\mu + \bar{\nu}_\mu$ CC. The distribution of the cosine of reconstructed zenith and the distribution of the reconstructed radial vertex position are shown in Fig. 2a and Fig. 2b respectively.

Data	Atm.μ	$\nu_e + \bar{\nu}_e$ CC	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_\tau + \bar{\nu}_\tau$ CC	$\nu + \bar{\nu}$ NC
3894	23	552	2958	162	222

Table 1: Number of data and MC simulated events of the final selection.

4. Unfolding of the $\nu_\mu + \bar{\nu}_\mu$ CC energy spectrum

The energy spectrum of the $\nu_\mu + \bar{\nu}_\mu$ CC selected events is unfolded from the reconstructed energy distribution, shown in Fig. 3a. The TUnfold software [5] was used for the implementation

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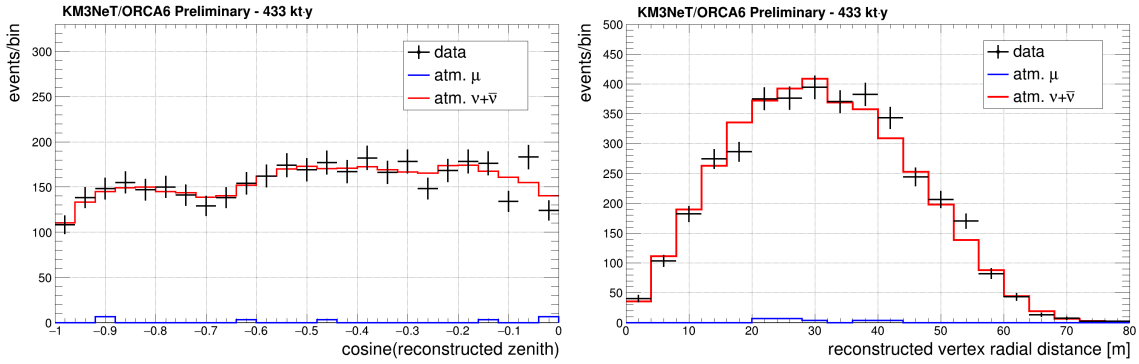

(a) Reconstructed cosine zenith.

(b) Reconstructed vertex radial distance.

Figure 2: Event variable distributions for the neutrino selection.

of the unfolding procedure. The unfolded spectrum is estimated using a least square method with Tikhonov regularization and a constraint on the total number of events. TUnfold also allows for a subtraction of background events using the estimation from the MC simulation. As the spectrum to be unfolded is that of $\nu_\mu + \bar{\nu}_\mu$ CC events, the shower-like atmospheric $\nu_e + \bar{\nu}_e$ CC, $\nu_\tau + \bar{\nu}_\tau$ CC, and $\nu + \bar{\nu}$ NC, as well as the (negligible, sub-percent) contribution of atmospheric muon events that survive the selection criteria are subtracted within TUnfold. Moreover, to account for the limited instrumented volume of the ORCA6, as an early configuration of KM3NeT/ORCA, the contribution of events with $E_\nu > 100$ GeV is treated as an overflow to the measured energy spectrum within TUnfold. As a result, the flux measurement is performed in the range between 1 GeV and 100 GeV.

The choice of the binning of the unfolding procedure is determined according to the bin purity. The bin purity is defined as the fraction of events in a bin of the reconstructed energy, for which the true energy belongs to the same bin. Three bins for the true neutrino energy were selected as $\log_{10}(E_\nu/\text{GeV}) : \{0.0, 0.7, 1.3, 2.0\}$. The purities for the bins $\log_{10}(E_\nu/\text{GeV}) \in (0, 0.7), (0.7, 1.3), (1.3, 2.0)$ are 58%, 55% and 79% respectively.

The results of the unfolding procedure are presented in Table 2. The unfolded energy distribution for the atmospheric $\nu_\mu + \bar{\nu}_\mu$ CC events is shown in Fig. 3b, while the MC truth has been added as a reference.

$\log_{10}(E_\nu/\text{GeV})$	Unfolded	MC $\nu_\mu + \bar{\nu}_\mu$ CC	statistical error
0.0 – 0.7	194	202	± 16%
0.7 – 1.3	540	680	± 6%
1.3 – 2.0	1055	948	± 5%

Table 2: Number of events for the unfolded energy spectrum and statistical unfolding errors. The number of MC simulated events for each bin in true (MC) neutrino energy has been also added as a reference.

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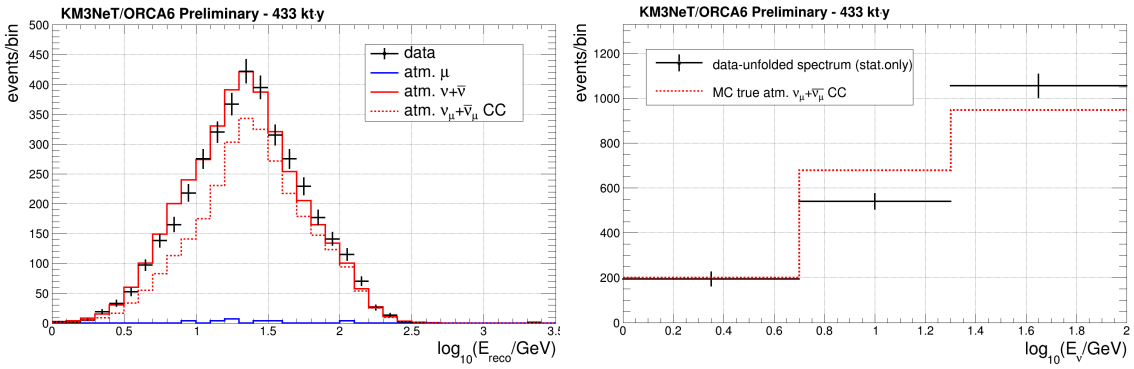

(a) Reconstructed energy for selected events.

(b) Unfolded and true energy for $\nu_\mu + \bar{\nu}_\mu$ CC events.

Figure 3: Reconstructed energy for selected events (*left*,3a). Unfolded and true energy for $\nu_\mu + \bar{\nu}_\mu$ CC events (*right*,3b).

5. Flux measurement

The number of events unfolded from data for each energy bin are converted into flux values. The atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux for each energy bin i is calculated as:

$$\Phi_i = \Phi_{\mathrm{MC}}^{\nu_\mu+\bar{\nu}_\mu}(\tilde{E}_i) \cdot \frac{N_i^{\mathrm{unfolded}}}{N_{i,\,\mathrm{MC}}^{\nu_\mu+\bar{\nu}_\mu\,\mathrm{CC}}} \tag{1}$$

with N_i^{unfolded} and $N_{i,\,\mathrm{MC}}^{\nu_\mu+\bar{\nu}_\mu\,\mathrm{CC}}$ being the number of unfolded and the number of MC simulated $\nu_\mu + \bar{\nu}_\mu$ CC events per bin respectively, and $\Phi_{\mathrm{MC}}^{\nu_\mu+\bar{\nu}_\mu}(\tilde{E}_i)$ the average in zenith and azimouth of the expresion:

$$\sum_{\nu_i=\nu_e,\nu_\mu} \Phi_{\mathrm{MC}}^{\nu_i}(E_\nu,\theta,\phi) \cdot O^{\nu_i\to\nu_\mu}(E_\nu,\theta) + \Phi_{\mathrm{MC}}^{\bar{\nu}_i}(E_\nu,\theta,\phi) \cdot O^{\bar{\nu}_i\to\bar{\nu}_\mu}(E_\nu,\theta) \tag{2}$$

calculated at the weighted bin centers $\tilde{E}_i$. $O^{\nu_i\to\nu_j}$ is the oscillation probability from a flavour i to a flavour j, and $\Phi_{\mathrm{MC}}^{\nu_i}$, $\nu_i = \nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$ are the predicted fluxes according to HKKM14.

The systematic uncertainties on the flux estimate are evaluated by repeating the unfolding procedure, after modifying the neutrino weights to account for uncertainties related to detector response (PMT efficiencies, light absorption length), hadronisation in cosmic ray extensive air showers, neutrino cross section, unfolding procedure, and light simulation. The difference between the obtained flux and the nominal measured flux per bin is considered as the systematic uncertainty. The overal systematic uncertainty for each bin is considered as the sum in quadrature of the several uncertainties.

The results are presented in Table 3, and are also shown in Fig. 4, superimposed with measurements from Super-Kamiokande [6], ANTARES [7] (beyond 100 GeV), and Frejus [8] (performed before the discovery of neutrino oscillations). For $0.7 < \log_{10}(E_\nu/\mathrm{GeV}) < 1.3$, the measured value is $\sim 20\%$ lower with respect to the HKKM14 flux (Eq. 2), while the measurement from Super-Kamiokande also indicates $\sim 15\%$ lower values for $0.6 < \log_{10}(E_\nu/\mathrm{GeV}) < 1.0$.

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$\log_{10}(E_\nu/\mathrm{GeV})$	$\log_{10}(\tilde{E}_i/\mathrm{GeV})$	$\tilde{E}_i^2\Phi_i$	stat. error	syst. error
0.0 – 0.7	0.41	$1.29 \cdot 10^{-2}$	±16%	$^{+26\%}_{-32\%}$
0.7 – 1.3	0.87	$4.49 \cdot 10^{-3}$	±6%	$^{+23\%}_{-25\%}$
1.3 – 2.0	1.50	$1.83 \cdot 10^{-3}$	±5%	$^{+25\%}_{-29\%}$

Table 3: Energy range; energy weighted bin center; measured flux multiplied by the energy weighted bin center, measured in GeV $\cdot$ s^{-1} $\cdot$ sr^{-1} $\cdot$ cm^{-2}; statistical uncertainty; systematic uncertainty.

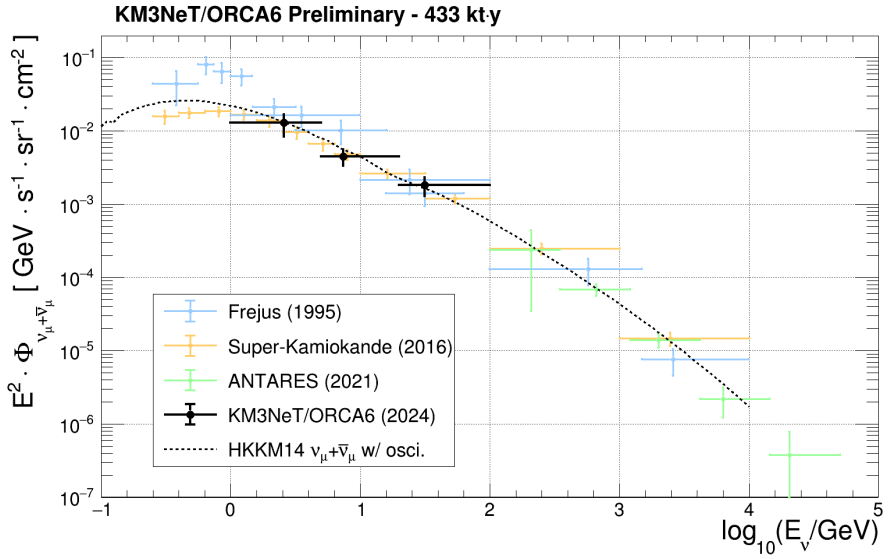

Figure 4: The atmospheric muon neutrino flux measurement using KM3NeT/ORCA6 data is shown along with other measurements.

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