PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

Atmospheric neutrinos with the first KM3NeT/ORCA data and prospects for measuring the atmospheric neutrino flux

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KM3NeT 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 near Toulon, France. It consists of vertical structures (Detection Units) equipped with spherical Digital Optical Modules, each hosting a set of photomultiplier tubes capable of detecting neutrino events from the Cherenkov radiation induced by the daughter particles. In this contribution, an analysis of data collected with the first 6 Detection Units (ORCA6) leading to a sample of atmospheric neutrino events is described. The angular resolution and the energy reconstruction performance for this event selection, which is a key factor for measuring the atmospheric neutrino flux are presented.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

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PoS(ICRC2021)1125

1. Introduction

The KM3NeT Collaboration is currently constructing a research infrastructure in the depths of the Mediterranean Sea [1]. This research infrastructure consists of two detectors with different scientific goals. The ARCA (*Astroparticle Research with Cosmics in the Abyss*) detector is located offshore of Sicily, Italy, at a maximum depth of 3450 m. The primary goal of this detector is to perform neutrino astronomy by detecting high energy astrophysical neutrinos (E > TeV). The other detector, ORCA (*Oscillation Research with Cosmics in the Abyss*) is located 40 km offshore Toulon, France, at a depth of 2450 m. The primary goal of ORCA is to measure the neutrino mass ordering, by being sensitive to oscillations of atmospheric neutrinos in the energy range of a few GeV.

The KM3NeT/ORCA detector is an array of photomultiplier tubes (PMTs), capable of detecting neutrino events via the Cherenkov radiation emmited by the daughter particles. These 3-inch diameter PMTs are found in groups of 31, into high-resistance glass spheres called Digital Optical Modules (DOMs), in order to endure the pressure at the abyssal depths (Fig.1). The DOMs contain also the required electronics for the operation of the PMTs, the data transmission as well as instruments for the orientation, position and time calibration [2]. The DOMs are tied together in groups of 18 forming vertical structures, the so-called Detection Units (DUs - Fig.2). Each DU is anchored to the seabed and remain vertical due to the buoyancy of the DOMs as well as of a buoy which is tied on its top. The vertical distance between the DOMs in a DU is ~ 9 m, and the horizontal distance between the DUs is ~ 20 m. When completed, the ORCA detector will consist of 115 DUs, forming a cylindrical instrumented volume with a radius ~ 100 m, and height ~ 160 m. The ARCA detector will be similar to ORCA, with a sparser instrumentation as it aims to be sensitive to higher energy neutrinos of astrophysical origin.

Figure 1: The Digital Optical Module, with 31 PMTs distributed on its surface.

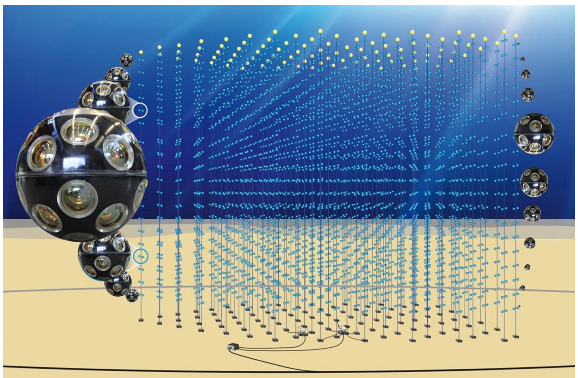

Figure 2: Artistic view of the full KM3NeT/ORCA detector. The vertical structures are the DUs on which the DOMs are attached.

The KM3NeT/ORCA detector operates with 6 DUs (ORCA6) since January 2020. In these proceedings, an analysis of data collected with ORCA6 configuration that provides a sample of atmoshperic neutrinos is presented. The angular resolution and the energy reconstruction performance of this neutrino sample as well as the prospects for a measurement of the atmospheric neutrino flux are also discussed.

2. Detector status and data sample

In January 2020 two additional DUs were deployed, extending the already operational ORCA detector to the current 6-DU configuration. At present, the instrumented volume of ORCA6 is ~ 136 kton. The layout of the ORCA6 detector is shown in Fig. 3, which depicts the footprints of the DUs on the horizontal plane.

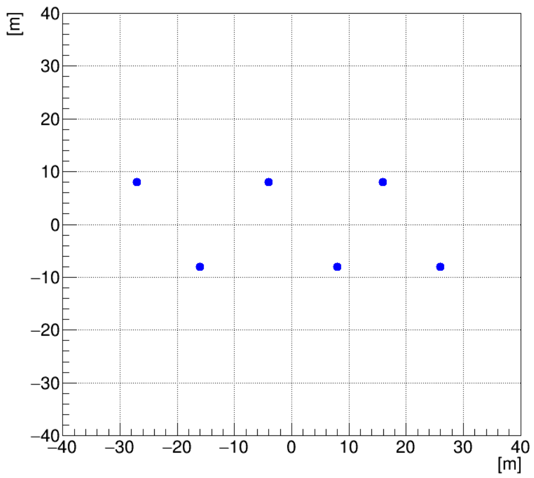

Figure 3: The DU footprints of the ORCA6 configuration.

The data used in this analysis were collected from February 11, 2020 to March 03, 2021. During this period the detector was operating 96% of the time. After a quality selection and rejection of data runs recorded for calibration and test purposes, the data sample obtained for this analysis is equivalent to 354.6 days. This corresponds to an overall 92% time efficiency with respect to the full-time period, as depicted in Fig. 4.

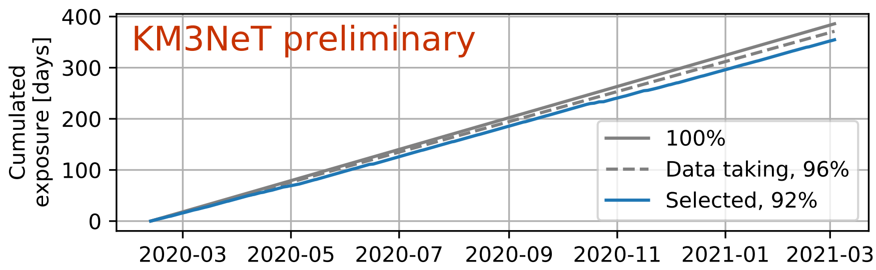

Figure 4: Cumulated exposure of overall time, data-taking time, and livetime of the selected data.

The selected data runs were processed and the events were reconstructed under the track hypothesis, using the KM3NeT software package Jpp [3].

3. Simulation of atmospheric neutrinos and muons

Events of atmospheric neutrinos and muons were simulated to evaluate the detector response. The followed strategy was to produce run-by-run simulation in which each run is simulated separately, in order to account for the variation of the detector and data-taking conditions.

For the generation of the simulated neutrino events, the gSeaGen GENIE-based software [4] was used. Neutrino and antineutrino events for charged current (CC) interactions for each flavor, as well as neutral current (NC) interaction events, were simulated. All the neutrino events were weighted using the HKKM2014 neutrino flux [5] computed for the Frejus location. Moreover, the oscillation probabilities were taken into account in the calculation of the neutrino weights. For this, the oscillation parameters were set according to NuFIT 5.0 [6], assuming normal ordering for the neutrino mass hierarchy. The atmospheric muon background events were generated using MUPAGE package [7]. The PMT response and the readout are simulated by means of a custom KM3NeT software. The digitised PMT output pulses are called as *hits*.

Similar to the events in data, the simulated events were reconstructed under the track hypothesis [3].

4. Neutrino event selection

Atmosperic neutrino events have been discriminated from the atmospheric muon background after applying several selection criteria. At first, a soft cut on the maximum value of the likelihood fit in the reconstruction procedure is applied. This is intended to reject poorly reconstructed events as well as events that are produced by noise hits.

After this pre-selection, only events with upgoing reconstructed direction are accepted. With the rejection of the reconstructed as downgoing events, the atmospheric muon background consists only of events that are mis-reconstructed. This results in a high suppression of the atmospheric muon contribution with the remaining background consisting only of events that are mis-reconstructed as upgoing. A set of selection criteria is applied then to the remaining events. These can be separated into three different categories:

- **signal-like hits related criteria**: The agreement between the event hits and the reconstructed track hypothesis is examined with these criteria. In more detail, a cut on the number of triggered hits which have been recorded too early with respect to what is expected according to the track hypothesis is applied; triggered hits are those that have caused the event triggering. A minimum number of DOMs with at least one hit ("signal-like hit") expected from the reconstructed track in terms of time resolution and of the distance between the emission point along the reconstructed track and the PMT position, is required.

- **quality of the reconstructed event**: The quality of the track reconstruction is evaluated from the likelihood function at its maximum fitted value. A cut is applied on the ratio of this likelihood value to the number of hits used in the reconstruction. Moreover, a minimum difference is also required between the likelihood of the upgoing reconstructed track and the likelihood of the best potential downgoing solution, if there is one. An additional cut on the likelihood is applied, with the minimum required likelihood value to be proportional to the distance between the event's reconstructed vertex position and the detector's barycenter on the horizontal plane.

- **containment**: The position of the reconstructed vertex of the event should be closer than 60 m to the barycenter of the detector, on the horizontal plane. The mean height of the triggered hits should be above the height of the event's reconstructed vertex position, as well as above 55 m above the seabed.

The distribution of the reconstructed energy is shown in Fig. 5 after applying the described selection criteria. A final cut is applied at this point, rejecting the events with a reconstructed energy above 100 GeV. This is to account for the limited instrumented volume of the ORCA detector at this early stage of the construction.

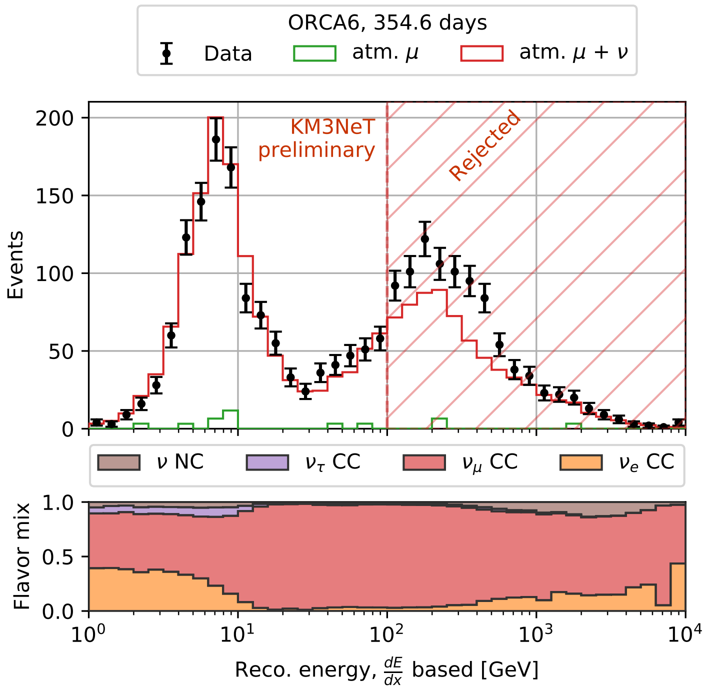

Figure 5: Distribution of the reconstructed energy for data and simulated events after applying all the selection cuts. The flavor mix for the atmospheric neutrino simulated events is also depicted for each energy bin.

The number of data events surviving the selection criteria and the reconstructed enegy cut is 1247, while 1240 ± 35 events are expected. This simulated neutrino sample consists of 223 $\nu_e + \bar{\nu_e}$ CC events, 902 $\nu_\mu + \bar{\nu_\mu}$ CC events, 70 $\nu_\tau + \bar{\nu_\tau}$ CC events as well as 45 NC events. A small contamination of simulated atmospheric muon events is expected, as 31 ± 10 events are expected to survive the selection criteria.

The distribution of the cosine of the reconstructed zenith angle is shown in Fig. 6 for the events that survive the pre-selection likelihood cut, as well as for the events that survive all selection criteria and the reconstructed energy cut. In Fig. 7, the detection rate for the selected events is presented as a function of time, accompanied by the respective residuals.

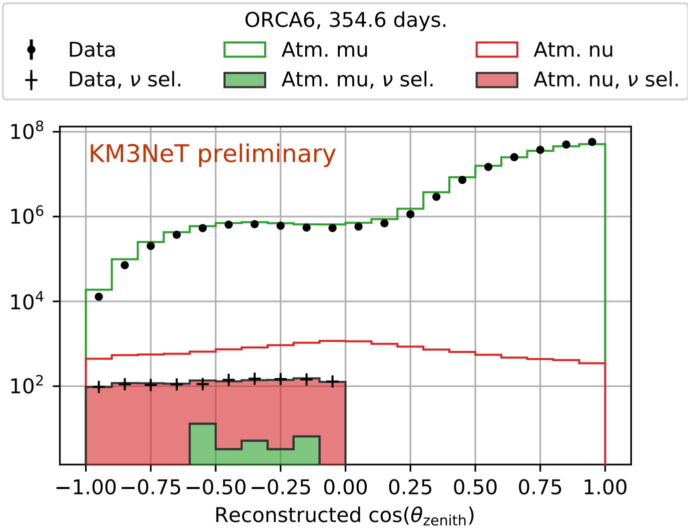

Figure 6: Distribution of the cosine of the reconstructed zenith angle for data and simulated events, after the pre-selection and for the final selection cuts.

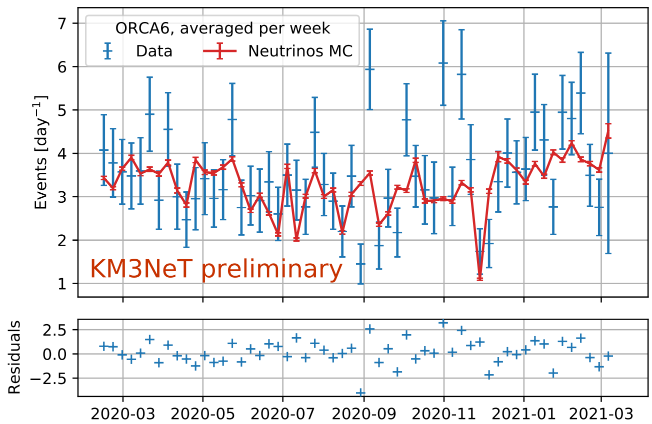

Figure 7: Selected events per day (averaged per week) for data and simulated events along with the respective residuals.

5. Resolution and prospects

The selected Monte Carlo (MC) neutrino events illustrate a good reconstruction performance. The angular resolution is presented in Fig. 8, as a function of the simulated neutrino energy. The angular resolution is better than 20° for energies greater than 4 GeV and better than 10° for energies greater than 20 GeV.

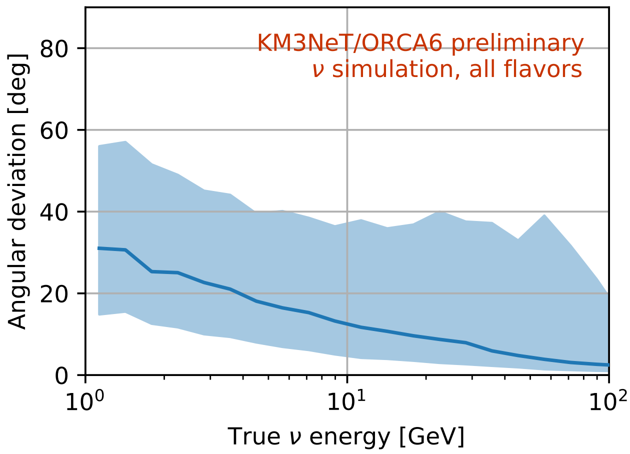

Figure 8: Angular resolution as a function of the neutrino energy for the MC selected neutrino events. The angular resolution is better than 10° for energies greater than 20 GeV. The band represents $\pm 1\sigma$ uncertainty.

The relationship between the true and the reconstructed energy is described in Fig. 9, where two different curves are shown. The first one represents the neutrino energy estimation using the detected light in a cylinder centred to the reconstructed track (*blue*). The other (*orange*) represents the energy estimation using the length of the reconstructed track multiplied by the expected energy loss per meter.

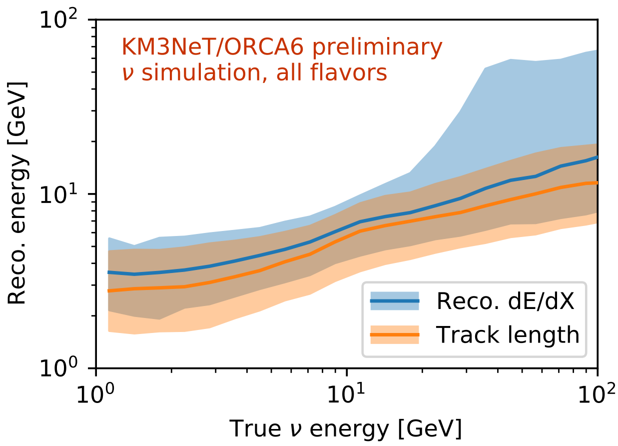

Figure 9: Median reconstructed energy as a function of the neutrino energy for the MC selected events. The bands represent $\pm 1\sigma$ uncertainty.

The neutrino energy reconstruction performance of the current detector configuration is constrained by its limited size. The upcoming deployments of more detection units will lead to an increase of the energy range and an improvement of the energy reconstruction, as longer tracks will be reconstructed more accurately and a larger fraction of fully contained events will be detected. This improvement will be an important step towards the measurement of the atmospheric neutrino flux. Such a measurement is important in order to test the Cosmic Ray models. The ORCA detector is sensitive to an energy range (1-100 GeV) in which there is room for improvement with respect to current experiments. As it is shown in Fig. 10, there exist few measurements especially between 10 and 100 GeV.

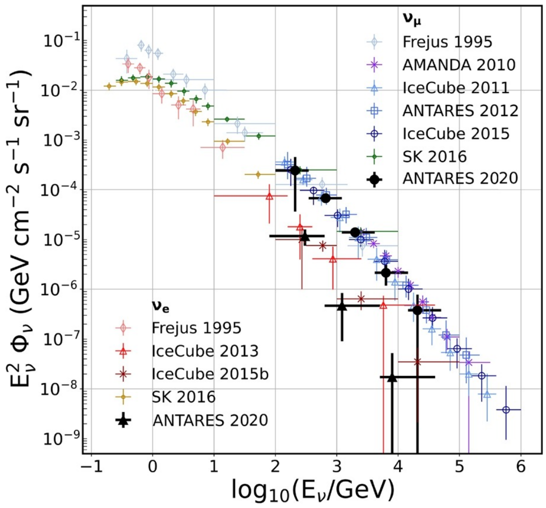

Figure 10: Measurements of the atmospheric neutrino flux by several experiments [8].

6. Conclusions

An analysis of ORCA6 data which results in a neutrino sample of high purity has been presented. The data period analysed corresponds to 354.6 days, with a 92% time efficiency with respect to the full-time period. The application of several selection criteria leads to 1247 events in data, while 1240 ± 35 events are expected from the simulation of atmospheric neutrinos and 31 ± 10 events from the atmospheric muon simulation. The angular resolution for the expected neutrinos has also been presented, demonstrating a good performance with respect to the early phase of construction. The current performance of the energy reconstruction has also been discussed. This is expected to improve considerably as more detection units are deployed.

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