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Event reconstruction in the KM3NeT/ORCA detector

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KM3NeT/ORCA is a megaton-scale underwater Cherenkov detector optimised for the neutrino mass hierarchy determination achieved by measuring the energy and zenith-angle dependent oscillation pattern of few-GeV atmospheric neutrinos. Event reconstruction is a key task and the achieved performance substantially affects the mass hierarchy sensitivity. The excellent optical properties of deep-sea water allow for accurate reconstruction of both shower-like (mostly electron-neutrinos) and track-like events (mostly muon-neutrinos).

This paper describes the key ingredients of the expected neutrino detection performance of ORCA. A focus is put on the methodology and performance of the reconstruction for shower-like events. In addition, the track-shower separation capability is presented.

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1. KM3NeT/ORCA – neutrino oscillation physics in the deep-sea

The KM3NeT collaboration has started the construction of two next-generation underwater neutrino telescopes in the Mediterranean Sea, named ARCA and ORCA. The two detectors share the same technology but target different neutrino energy regimes and physics goals. ORCA, to be installed in a depth of 2450 m offshore Toulon in France, is a dense megaton-scale detector optimised for measuring the oscillation of atmospheric neutrinos. ARCA, to be installed in a depth of 3500 m offshore Sicily in Italy, is a sparse gigaton-scale detector optimised for high-energy neutrino astronomy. The key KM3NeT technology is the Digital Optical Module (DOM), a pressure-resistant glass sphere housing 31 3-inch PMTs and their associated electronics. The DOMs are arranged in strings held vertically by a submarine buoy and anchored to the seabed.

The ORCA detector will consist of 115 such detection strings. Each string comprises 18 DOMs with a vertical spacing of roughly 9 m. The horizontal spacing between adjacent strings is about 20 m. With this detector layout, a mass of about 6 Mton of seawater is instrumented.[1] ORCA's main science goal is the determination of the neutrino mass hierarchy (NMH), which refers to the two possible orderings of the neutrino mass eigenstates. The NMH can be determined by measuring the energy and zenith-angle dependent oscillation pattern of few-GeV atmospheric neutrinos that have traversed the Earth towards the detector. The detector performance substantially affects the NMH sensitivity and event reconstruction is therefore a key task.

This contribution is mainly based on the 'Letter of Intent for KM3NeT 2.0' [1] and Ref. [2].

2. Event reconstruction in ORCA

The information available for event reconstruction in ORCA is a set of *hits*, which comprise the arrival time (nanosecond precision) of the detected photons and a charge information of the electrical pulse recorded by a PMT. The DOM positions ($\sim$ 10 cm precision) and orientations (few-degree precision) are monitored with calibration devices. The task of the event reconstruction is to find the event hypothesis that fits the observed hit pattern best. By this, the energy and direction of the incoming neutrino as well as other parameters of the neutrino interaction are reconstructed.

Two distinct event topologies are considered: tracks and showers. Showers are initiated by energetic electrons and hadrons emerging from the neutrino interaction. While showers develop over relatively short distances, energetic muons produce long tracks in the detector. Hence, track-like events are induced by $\overset{(-)}{\nu}_\mu$ charged-current (CC) interactions, as well as $\overset{(-)}{\nu}_\tau$ CC interactions with muonic tau decays. All other neutrino-induced events are called shower-like, i.e. from $\overset{(-)}{\nu}_e$ CC events, $\overset{(-)}{\nu}_{e,\mu,\tau}$ neutral-current (NC) and $\overset{(-)}{\nu}_\tau$ CC interactions with non-muonic tau decays.

Dedicated reconstruction algorithms for track-like and shower-like events, as well as for event topology classification, have been developed within KM3NeT/ORCA. The methodology and performance of the shower reconstruction and the event topology classification are described in the following. The performance of the track reconstruction is comparable to that of the shower reconstruction. Further details can be found in Ref. [1] and references therein.

[1] Currently, an increased inter-string spacing of 23 m is considered. This new detector configuration is $\sim$ 1.4 times larger in volume with a correspondingly smaller instrumentation density.

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2.1 Shower reconstruction

The shower reconstruction is performed in two steps. In the first step, the interaction vertex (time and position) is reconstructed based on the hit times and positions. In the second step, the direction, energy and inelasticity (or Bjorken y) are reconstructed based on the number of hits and their distribution in the detector. In both steps a maximum likelihood fit is performed for many different initial shower hypotheses and the solution with the best likelihood is chosen. Due to the large scattering length ($\lambda_s^{\mathrm{eff}} = \lambda_s / [1 - \langle\cos(\theta_s)\rangle] \approx 265\,\mathrm{m}$ for a photon wavelength of 470 nm) in deep-sea water the light emission characteristics are conserved over sufficiently large distances, so that information from a large detector volume (large lever arm) can contribute to event reconstruction, resulting in good resolutions. The precise vertex reconstruction ($0.5 - 1$ m) without prior knowledge of the shower direction justifies the factorisation of the fitting procedure.

The reconstruction is designed to find the electron direction in $\overset{(-)}{\nu}_e$ CC events, as the electron mostly is the dominant particle producing the brightest Cherenkov cone in the event and the number of detected photons is usually insufficient to independently resolve the Cherenkov cones from all particles emerging from the neutrino interaction. An example distribution of the expected number of photons as a function of the angle between the shower direction and the vector from the vertex to a photosensor is shown in Fig. 1 (left). The electron direction is used to define this angle. A clear Cherenkov peak of the electron at 42° is visible. With larger inelasticity, this peak becomes fainter due to less energetic electrons, while the number of expected photons in the 'off-peak region' increases due to the more energetic hadronic showers. This shape difference provides sensitivity to the inelasticity. The shower energy is inferred from the light yield, which is approximately proportional to the energy.

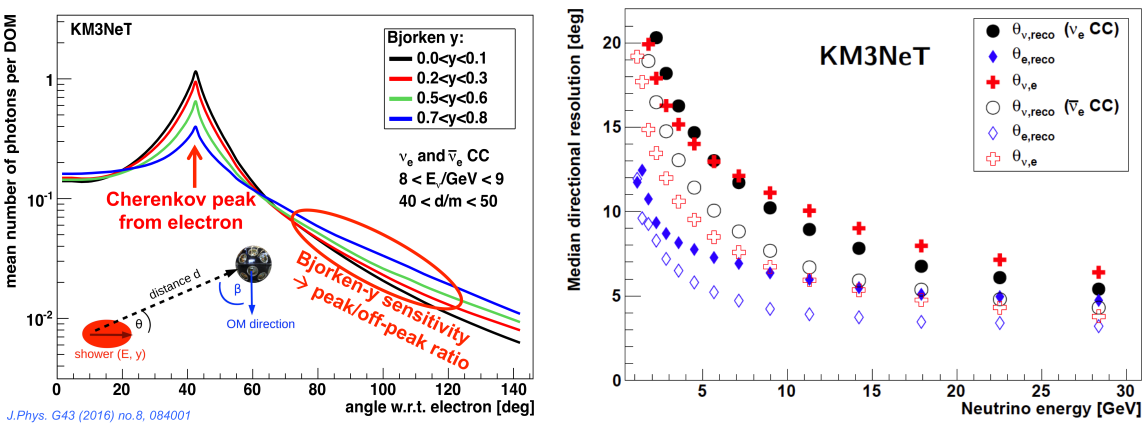

Figure 1: Left: number of expected photons detected by all PMTs in a DOM as a function of the angle between the electron direction and the vector from the vertex to a DOM for $\overset{(-)}{\nu}_e$ CC events in different intervals of inelasticity y, and for neutrino energies of $8 < E_\nu/\mathrm{GeV} < 9$ and at distances of $40 < d/\mathrm{m} < 50$. Right: median neutrino direction resolution (black circle), median ν-e scattering angle (red cross) and median electron direction resolution (blue diamond) as a function of neutrino energy for upward-going ν_e CC (filled marker) and $\bar{\nu}_e$ CC events (empty marker). These resolutions are for a more-densely instrumented detector assumed in Ref. [1] with 6 m instead of 9 m vertical spacing between the DOMs, however very similar resolutions are achieved for the 9 m configuration, as the neutrino direction resolution is dominated by the intrinsic ν-e scattering angle. Both figures are taken from Ref. [1].

The median neutrino direction resolution is better than $\sim 10^\circ$ for $\overset{(-)}{\nu}_e$ CC events with $E_\nu \gtrsim$ 10 GeV and is shown in Fig. 1 (right). The reconstruction is able to find the electron direction in $\overset{(-)}{\nu}_e$ CC events, and the resolution on the neutrino direction is limited by the intrinsic ν-e scattering kinematics. The energy resolution is Gaussian-like with $\sigma_{E_\nu}/E_\nu \approx 25\%$ for $\overset{(-)}{\nu}_e$ CC events with $E_\nu = 10$ GeV, and slightly improving with increasing energies. As discussed in Ref. [3], the energy resolution is dominated and therefore limited by intrinsic light yield fluctuations in the hadronic shower. The effective mass of the detector is about 6 Mton, which is reached for $\overset{(-)}{\nu}_e$ CC events with $E_\nu \gtrsim 10$ GeV, while 50% efficient at $E_\nu \approx 4$ GeV. For shower-like events other than $\overset{(-)}{\nu}_e$ CC, the detector performance is similar when scaling to the deposited energy which is different from the incoming neutrino energy for $\overset{(-)}{\nu}_{e,\mu,\tau}$ NC and $\overset{(-)}{\nu}_\tau$ CC events due to the invisible outgoing neutrinos.

2.2 Track–shower seperation

A trained classifier is used to assign the events to one of these three classes: "track-like" and "shower-like" neutrino events, and "atmospheric muons". The latter class accounts for downward-going muons coming from cosmic ray air showers which are misreconstructed as upward-going.

The track-shower discrimination is applied after the reconstructions and is based on reconstruction observables and hit time distributions. A machine-learning algorithm based on the "Random Decision Forest" technique is used as classifier . The performance is summarised in Fig. 2. At $E_\nu = 10$ GeV, about 80% (60%) of the ν_μ CC ($\bar{\nu}_\mu$ CC) events are correctly classified as tracks, while only 10% to 20% of the $\overset{(-)}{\nu}_e$ CC, $\overset{(-)}{\nu}_{e,\mu,\tau}$ NC and $\overset{(-)}{\nu}_\tau$ CC events are wrongly classified as tracks. Atmospheric muons are suppressed to a few percent contamination in the final neutrino event sample.

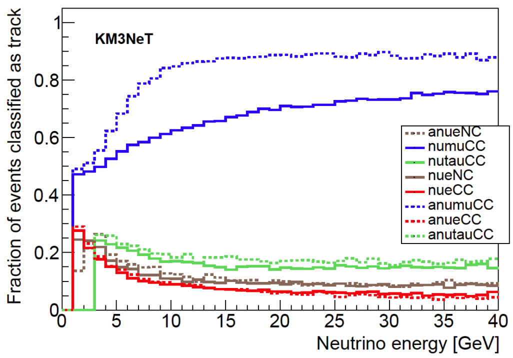

Figure 2: Fraction of events classified as "track-like". Figure taken from Ref. [1].

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References

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