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KM3NeT/ORCA status and plans

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Abstract. Neutrinos created in interactions of cosmic rays with the atmosphere can serve as a powerful tool to unveil the neutrino mass hierarchy (NMH). At low energies, around a few GeV, matter effects from the transition through the Earth are expected to imprint a distinct but also subtle signature on the oscillation pattern, specific to the ordering of the neutrino masses. KM3NeT/ORCA (Oscillations Research with Cosmics in the Abyss), a densely instrumented building block of the upcoming KM3NeT neutrino telescope, will be designated to measuring this signature in the Mediterranean Sea. Using detailed simulations the sensitivity towards this signature has been evaluated. The multi-PMT detectors allow in the water for an accurate reconstruction of GeV neutrino event signatures and distinction of neutrino flavours. For the determination of the mass hierarchy a median significance of 2-6σ has been estimated for three years of data taking, depending on the actual hierarchy and the oscillation parameters. At the same time the values of several oscillation parameters like θ_{23} will be determined to unprecedented precision.

1. Introduction

Neutrino physics provides for an exciting opportunity to advance our current understanding of fundamental particles and interactions, as several open questions are yet to be answered for these elusive particles. Though there exists, by now, significant evidence for their non-zero masses from oscillation measurements, the ordering of the masses has not yet been determined and also the Majorana/Dirac nature of the masses as well as the possible CP-phase in the mixing matrix are unknown. Two modes of possible mass ordering are distinguished whereby one is commmonly called the *normal hierarchy* (NH, $m_{\nu 3} > m_{\nu 1}$) and the other the *inverted hierarchy* (IH, $m_{\nu 1} > m_{\nu 3}$). The sensitivity of upcoming experiments will within the next decade improve to a level that the neutrino mass hierarchy (NMH) can be determined.

Abundant neutrinos are created in interactions of cosmic rays with the atmosphere and measured with current neutrino telescopes. An expansion of the sensitivity of the neutrino telescopes towards low energies of a few GeV will give access to an energy range in which the NMH influences the oscillation pattern sufficiently to be identified [1]. Matter effects during the passage of the neutrinos through the Earth affect the transition probabilities for the different neutrino flavours depending on the NMH.

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However, the impact on the oscillations is for NH and IH opposite for neutrinos and antineutrinos, which cannot be distinguished in a neutrino telescope. Still since the neutrino and antineutrino fluxes from the atmosphere are not exactly equal and also the neutrino cross section is about a factor of two larger than the antineutrino cross section [2] a net signature specific to the NMH remains in the oscillation pattern and can be measured.

2. Detector

The feasibility of neutrino studies with an underwater neutrino telescope has already successfully been demonstrated by the ANTARES neutrino telescope which is operational in the Mediterranean Sea since 2007 [3]. Building on this experience the KM3NeT research infrastructure [4] has been planned and is currently under construction. It will host two neutrino telescope installations: ARCA (Astroparticle Research with Cosmics in the Abyss) at an Italian site located about 100 km from Capo Passero (Sicily, Italy) at a depth of 3500 m, focussed on the measurement of high energetic astrophysical neutrinos and ORCA (Oscillations Research with Cosmics in the Abyss) at a French site located about 40 km from Toulon (France) at a depth of 2475 m, focussed on low energetic atmospheric neutrinos. The same technology will be used at both sites but different detector densities will be implemented optimized for the different addressed energy ranges.

A pressure resistant glass sphere of 17 inch diameter (Digital Optical Module – DOM), which hosts 31 3″ photomultipliers (PMTs) distributed to cover all directions, is the active sensor of the telescope [5]. For the PMT signals a nanosecond timing precision is achieved and all time-over-thresholds of these signals are sent to shore for further processing and filtering. Calibration tools are implemented to determine in real-time the position of the detectors to the precision of a few centimeters and the orientation within a few degrees.

The small PMTs allow for single photon counting and signal correlations enable powerful background rejection of photons from bioluminiscence or from the radioactive decays of ^{40}K in the seawater. The homogeneously distributed ^{40}K signal is not only considered a background but serves also as a constant calibration source to determine the time offsets on a DOM and enables continuous monitoring of the PMT performance [6].

The DOMs are distributed on strings which are fixed on the floor and kept taut by a buoy. One string contains 18 DOMs whose distance determines the accessible energy range. For ORCA the DOM distance on a string is currently being optimized in the range of 6 m to 18 m. The results shown in this contribution have been determined for a distance of 6 m. The distance between the strings is for ORCA fixed to 20 m according to deployment constraints.

In December 2014 the first main electro-optical cable was successfully deployed at the French Site followed by the deployment of the first junction box for the connection of strings in the summer 2015. The first 6 strings will be built and deployed by the end of 2016. The full ORCA array of 115 strings will then be constructed and become operational within three years depending on the availability of funds.

3. Simulations and event reconstruction

The possible measurement of the oscillation pattern has been studied using detailed simulations [7]. The neutrino and antineutrino interactions were generated with a software based on the GENIE [8] neutrino event generator. The weighting of the events follows the Bartol atmospheric neutrino flux model [9]. The background of down-going muons was generated using the MUPAGE [10] program. All particles in the vicinity of the detector are propagated with a GEANT based software package. This generates Cherenkov light from primary and secondary particles whereby the effects of absorption and scattering in water as well as the characteristics from the PMTs are taken into account in the propagation and signal creation. Also photons from ^{40}K decays are added in the simulations.

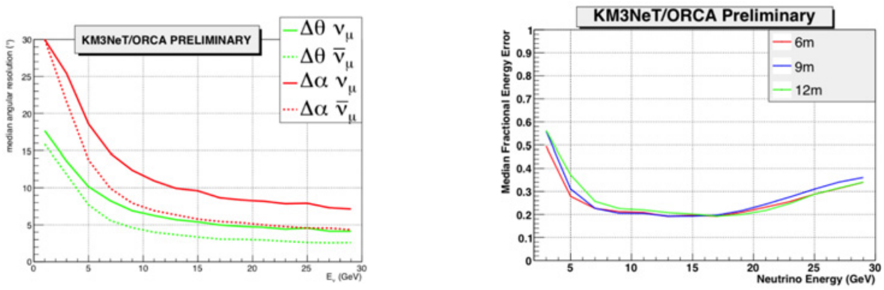

Figure 1. Left: The median angular resolution is shown for ν_μ events as a function of the neutrino energy for the neutrino direction α and the zenith angle θ. Right: The median energy resolution is shown as a function of the neutrino energy for different vertical DOM distances.

The main task of the reconstruction is to provide accurate information on the direction and energy of the neutrino as well as on the flavour. A neutrino interaction in the detector results in a track-like or a cascade-like signature. A charged current (CC) interaction of a ν_μ leads to the creation of a muon which leaves signals along its path in the detector and thus shows a track-like signature. The length of a 5 GeV muon track amounts to ~25 m. The ν_e and ν_τ CC interactions create an electron and a tau respectively, which both lead to the creation of a cascade and thus a cascade-like signature. The distinction of the track-like and the cascade-like signatures allows thus some flavour identification for the CC interactions. The neutral current (NC) interactions of neutrinos of all flavours result in a cascade at the interaction vertex and thus also a cascade-like signature. In this case no flavours can be distinguished and the NC interactions represent a background to the oscillation measurement.

The event signatures also depend on the inelasticity of the interaction as not all energy of the neutrino will be transferred to the final lepton which is taken into account in the reconstruction.

Both event signatures (track/cascade) are addressed with designated multi-step algorithms. Hits are selected based on timing correlations and for the track-like signature a grid of directions is evaluated with likelihood fits whereby the candidate with the best likelihood is chosen. The energy of the neutrino is estimated in the case of the track signature from the length of the reconstructed track as well as the associated hits. For the cascade, first the interaction vertex is determined, then the direction, energy and inelasticity using a likelihood fit.

The directional and energy resolution for the track reconstruction can be seen in Fig. 1. In the relevant energy range of 5–12 GeV the directional resolution is better than 10 degrees and the energy resolution better than 25%. The performance varies only slightly with the DOM distance and is similar for cascades.

The inelasticity y for ν_e CC interactions is determined in the likelihood fit from the amount of photons found at the Cherenkov angle with respect to the reconstructed direction as compared to the amount of photons at other angles. A comparison of the angle distributions of photons is shown in Fig. 2 separately for events from different inelasticity ranges. The Cherenkov photons from the electron lead to a prominent peak at the Cherenkov angle for events with low inelasticities.

For the ν_μ CC interactions the inelasticity is reconstructed from time residual distributions of the hits. The distributions are created with respect to the expectation of Cherenkov light from a track hypothesis and with respect to the expectation from shower light from the vertex. The dependence of these distributions on the inelasticity of the event is then exploited for the inelasticity determination. For both cascade and track interactions some sensitivity on the inelasticity could be gained but is also still being optimized. It is not yet used in the NMH determination but will be exploited in the future since it can increase the sensitivity as has been shown for ν_μ interactions [11].

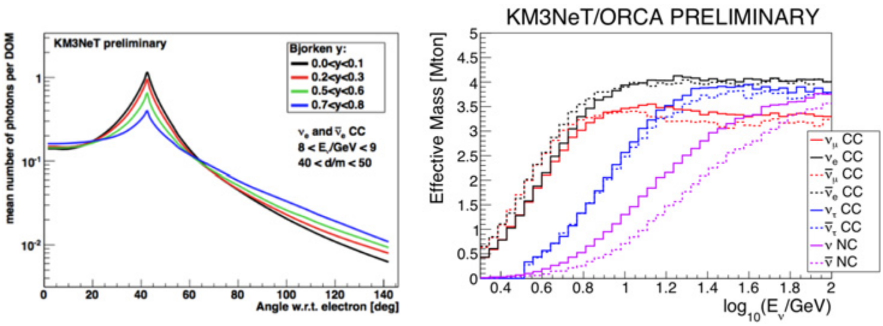

Figure 2. Left: The distribution of photon angles with respect to the electron direction is shown for ν_e events. Right: The effective mass is shown for the different (anti-)neutrino interactions.

An important parameter for evaluating the reconstruction performances and the sensitivity for the measurement of the neutrino mass hierarchy is the effective volume, defined as the volume of a perfectly efficient detector to observe neutrinos interacting within that volume. Figure 2 shows on the right side the effective mass from the reconstruction of the different neutrino interactions, obtained by multiplying the effective volume by the seawater density, equal to 1.025 g/cm^3. For an energy around 5 GeV the effective mass reaches the instrumented detector mass for ν_μ and ν_e CC interactions.

The identification of a track-like or cascade-like event is implemented using a random decision forest (RDF) classification [12]. Many characteristics of the event signatures like the likelihood values of the reconstruction or time residuals are exploited in this classification. For the important energy range between 5–12 GeV the identification succeeds in 80% of the antineutrino events, whereby this fraction rises with energy. The performance for neutrinos is slightly worse due to the different inelasticities of neutrino events compared to antineutrinos as on average less of the energy of the neutrinos will go to the muon. Cascades from ν_e interactions are misidentified as tracks in less than 10% of the cases and this fraction decreases strongly with energy.

The background from the abundant down-going muons is suppressed at first with basic cuts on the reconstructed zenith angle and vertex position. Only up-going events are selected and the vertex position is constrained to reside approximately in the instrumented volume. This decreases the amount of atmospheric muons by three orders of magnitude. Further suppression, by two orders of magnitude, is achieved by using a boosted decision tree (BDT) for the identification of these events. Only a few percent of misreconstructed muon events remain in the final sample of reconstructed events.

4. Sensitivity calculation

Using the atmospheric neutrino fluxes, the neutrino interaction cross sections and a model for the matter distribution in the Earth [13] the expected oscillation patterns can be calculated for the different mass hierarchies. From these the distinction of the hierarchies can be evaluated. More than ten thousand neutrino events are expected to be detected per year. The differences between the NH and IH oscillation patterns are of the order of a few percent in small energy-zenith regions, so that unprecedented control of systematics is mandatory.

The reconstruction performance together with the particle identification and background contamination is used to generate the oscillation pattern as a function of zenith and energy as pseudo-experiments for different oscillation parameters and hierarchies. For each oscillation pattern the likelihood for NH or IH is determined and a likelihood ratio calculated. The oscillation parameters are included in the fit. Parameters which had been shown to have little impact are kept fixed ($\theta_{12}, \theta_{13}, \Delta m^2$)

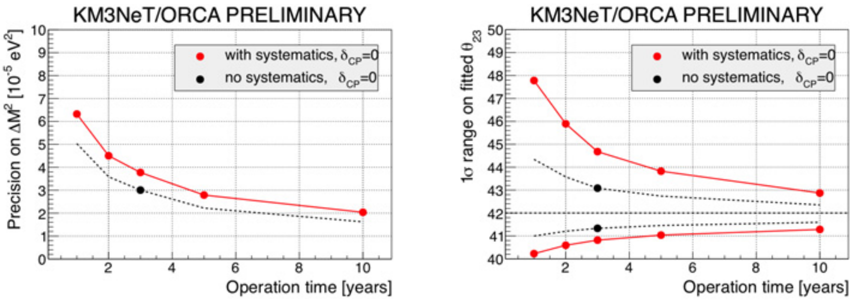

Figure 3. Left: The precision in ΔM^2 as determined in the measurement is shown as a function of the observation time. Right: Similar presentation for the precision on θ_{23}.

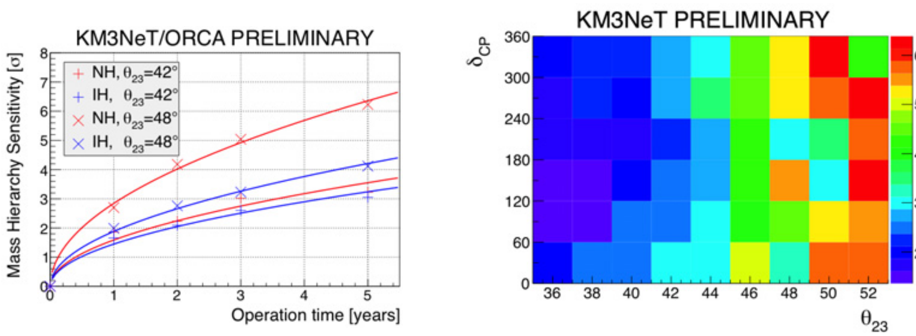

Figure 4. Left: The median significance of the NMH distinction is shown as a function of time for the different hypotheses and two different θ_{23} values. Right: The median significance of the measurement is shown for the NH as color scale as a function of the true δ_{CP} and θ_{23}.

while the others are fitted unconstrained ($\Delta M^2 = \frac{1}{2}(\Delta m^2_{32} + \Delta m^2_{31}), \theta_{23}, \delta_{CP}$). Figure 3 shows the development of the precision reached in the oscillation parameters ΔM^2 and θ_{23} as a function of the observation time. After three years the uncertainty on ΔM^2 will already only be half of the present uncertainty and also the uncertainty on θ_{23} will shrink similarly.

Aside from the oscillation parameters also the neutrino fluxes, cross sections and the hadronization impact the pattern. Many of these external uncertainties are parametrized and incorporated as nuisance parameters in the global fit, e.g. the overall normalization, the $\nu/\bar{\nu}$ ratio, the e/μ ratio, the NC scaling and the energy slope. The largest average fluctuation on these parameters with respect to a nominal simulation is found to be 11% for the NC scaling while for all other parameters fluctuations smaller than 4% are found. None of the considered systematics compromises the determination of the NMH.

The sensitivity towards the NMH is evaluated from the resulting likelihood ratio distributions in the pseudo experiments for NH and IH as a median significance, which is the significance for excluding the wrong hierarchy when the measured likelihood ratio is at the median of the true hierarchy distribution. The development of the sensitivity with observation time is shown in Fig. 4 for two different values of θ_{23} and the different hierarchies. On the right side of the figure the dependence of the significance on θ_{23} and δ_{CP} is shown for the NH, which ranges from 2–6σ in the currently most likely range for θ_{23}.

5. Conclusions

KM3NeT/ORCA will measure the flavour oscillations of atmospheric neutrinos to unprecented precision. The neutrino mass hierarchy impacts the oscillation pattern and can thus be determined with these measurements. The reconstruction of the neutrino event signatures and distinction of different flavour interactions were evaluated in detailed simulations and also a powerful background rejection could be demonstrated. The median significance to determine the NMH was evaluated to range from 2 to 6σ in three years depending on the oscillation parameters and hierarchy (NH or IH).

The sea infrastructure for ORCA is already being set up at the foreseen French site in the Mediterranean Sea and the first six ORCA strings will be deployed by the end of 2016. After this proof of the technology the full foreseen detector of 115 strings can then be completed within three years.

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