PROCEEDINGS OF SCIENCE

Status and Perspectives for KM3NeT/ORCA

Liam Quinn*, **on behalf of the KM3NeT Collaboration**
Centre de Physique des Particules de Marseille, France
E-mail: quinn@cppm.in2p3.fr

The KM3NeT Collaboration is constructing neutrino detectors at depths of 2475 m and 3400 m in the Mediterranean Sea, on scales up to a gigaton. These detectors, named ARCA and ORCA are each made up of a three-dimensional array of spherical optical modules. Each of them contains 31 3" photomultiplier tubes, designed to detect Cherenkov light emitted by charged leptons produced by neutrino interactions in and around the instrumented volume. These are packed either sparsely (ARCA) or densely (ORCA), depending on the target energy. ORCA, which is under construction off the coast of Toulon in France, will study atmospheric neutrino oscillations in the 1-100 GeV range. This will address multiple outstanding issues in neutrino oscillation research, including the determination of the neutrino mass hierarchy. Physics studies indicate that this can be determined with a significance of 3-7 sigma (depending on the true value of the hierarchy and the value of the mixing angle θ_{23}) after three years of operation.

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*Speaker.

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1. Introduction

The primary objectives of the KM3NeT Collaboration are the identification of sources of high-energy neutrinos in the universe and the determination of the neutrino mass hierarchy (NMH). Whilst neutrino transition probabilities in vacuum are not sensitive to the NMH, the ν_e component of the atmospheric neutrino flux can undergo charged-current elastic scattering with the electrons in matter. This introduces a dependence on the sign of Δm^2_{23} [1]. This matter effect is inverted for neutrinos and anti-neutrinos. However, a net asymmetry is still detectable due to the difference in the neutrino and anti-neutrino charged-current cross sections. Consequently, a Cherenkov neutrino detector on the Earth's surface is uniquely suited to NMH determination, studying atmospheric neutrinos (a free beam of known composition) over a range of energies and baselines [2].

The ORCA detector will be composed of 115 detection lines, each of which is made up of 18 spherical Digital Optical Modules (DOMs), deployed at a depth of 2475 m below sea level, approximately 40 km off the shore of Toulon. Each DOM is a glass sphere containing 31 3" photo-multiplier tubes (PMTs), designed to detect the Cherenkov signature of leptons created by neutrino interactions in the seawater. With a threshold of a few GeV, ORCA will measure the oscillated flux of atmospheric neutrinos passing through the Earth and will derive stringent constraints on the NMH as well as other oscillation parameters [3]. The sensitivity to the NMH, as published in the Letter of Intent [3], shall be presented in Section 2, in Section 3 constraints on the tau appearance shall be discussed, and finally in Section 4 there will be an update to the detector effective volume, as a consequence of the updated geometry and trigger.

2. Sensitivity to the Neutrino Mass Hierarchy

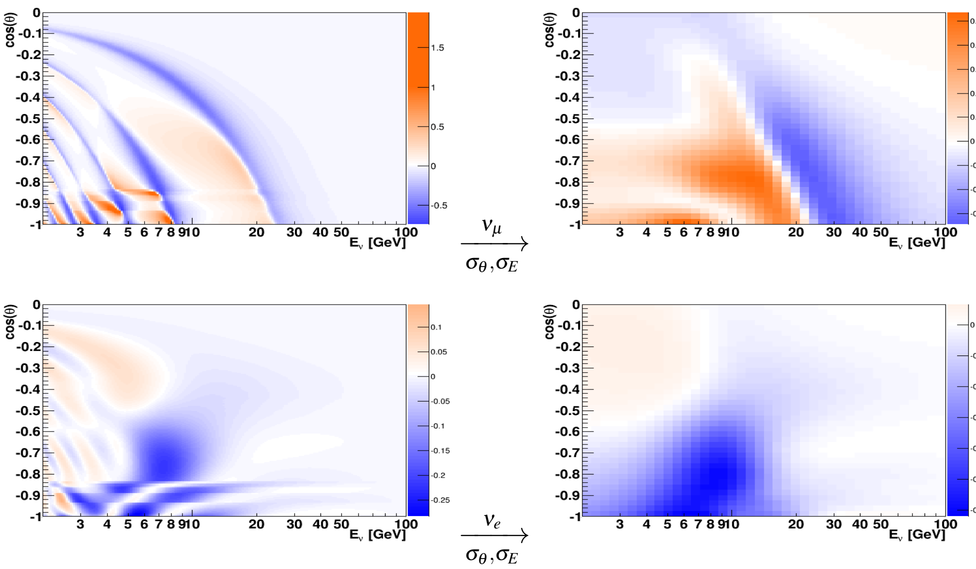

Figure 1: The asymmetry $\frac{N_{IH}-N_{NH}}{N_{NH}}$ for the muon and electron channels, before and after smearing according to the detector resolution.

In order to estimate the neutrino mass hierarchy (NMH) sensitivity, a full detector simulation has been developed, incorporating atmospheric neutrinos with the Bartol flux, atmospheric muon background, the trigger algorithms, water properties and PMT response [3], [4], [5], [6]. Dedicated reconstruction algorithms have been developed for events in the track (muon charged current) and shower (electron charged current and neutral current) channels. Finally, events are classified as either tracks or showers, using a random decision forest.

parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
θ_{23} [°]	$\{40, 42, \ldots, 50\}$	uniform over [35, 55] †	fitted	no
θ_{13} [°]	8.42	$\mu = 8.42$, $\sigma = 0.26$	fitted	yes
θ_{12} [°]	34	$\mu = 34$, $\sigma = 1$	nuisance	N/A
ΔM^2 [10^{-3} eV^2]	$\mu = 2.4$, $\sigma = 0.05$	$\mu = 2.4$, $\sigma = 0.05$	fitted	no
Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6$, $\sigma = 0.2$	nuisance	N/A
δ_{CP} [°]	0	uniform over [0, 360]	fitted	no
overall flux factor	1	$\mu = 1$, $\sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1$, $\sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0$, $\sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0$, $\sigma = 0.05$	fitted	yes

Figure 2: Default parameter settings used for the NMH analysis. Where μ and σ are given, they refer to a Gaussian distribution. The † indicates that seven initial values for θ_{23} are generated. They are $x + i \times 5°$, where x is either 35 or 55 and $i \in [-3, -2, ..., 3]$.

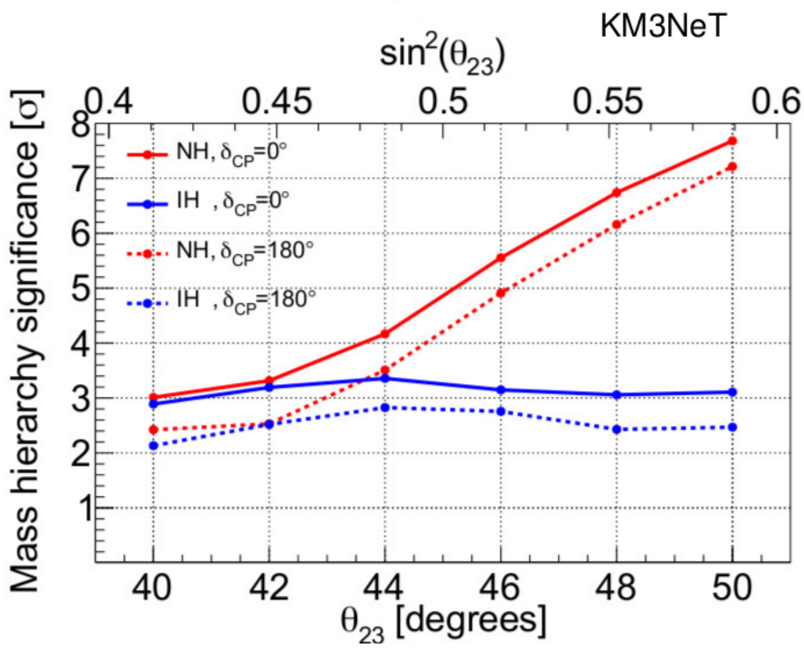

Figure 3: The ORCA sensitivity to the neutrino mass hierarchy after 3 years of data taking with a full detector, as reported in the KM3NeT LoI.

The NMH sensitivity is calculated using a likelihood ratio approach. For each pseudo experiment, a true value for the oscillation parameters and other systematics is selected and pseudo data is generated from the simulation chain, and finally the log likelihood is calculated for each mass hierarchy hypothesis. The full treatment of oscillation parameters and systematics is presented in Figure 2. A sensitivity of three sigma is expected after three years of operation with a full detector.

3. Tau Appearance

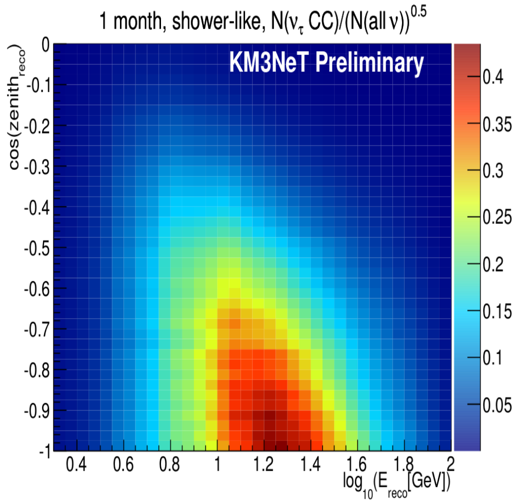

Figure 4a: The per-bin significance of the detected ν_τ signal for a month of events classified as showers.

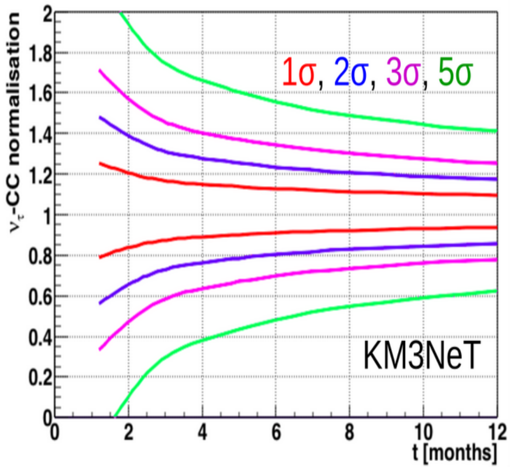

Figure 4b: Sensitivity of the ORCA detector to appearance of ν_τ as a function of time. For unitary mixing, the $\nu_\tau - CC$ normalisation is equal to one.

The ν_τ contribution to the atmospheric neutrino flux is negligibly small at creation, as it can only be created by the decay of mesons containing heavy quarks. Consequently, the ν_τ component measurable at the detector is only present because of oscillations. Due to the short lifetime of the tau, its creation and decay vertices cannot be resolved separately in ORCA. Instead, ν_τs will appear as an excess in the shower channel (see Figure 4a), the magnitude of which can be used to place constraints on the unitarity of PNMS matrix. ORCA will be able to confirm tau appearance with a confidence of 5σ within two months of operation. It will also be able to constrain the normalisation of the ν_τ flux within $\pm 20\%$ of unity, after a year of operation with a significance of 3σ (see Figure 4b).

4. New Trigger and Detector Geometry

Since the publication of the Letter of Intent in 2016, two notable changes have been made to the ORCA design and software. Firstly, the horizontal line spacing has been increased from 20 m to 23 m on average. Secondly, a new trigger algorithm has been designed. Previously, all trigger algorithms were based entirely on Level 1 (L1) hits, defined as a set of coincident photons on a single DOM within a time window of 10 ns. A minimum of three and four L1s are required for the standard shower and muon trigger respectively. In the sub GeV range, many reconstructible events do not pass this threshold, so the new algorithm requires only a single L1 and then looks for coincidences between single photons on multiple DOMs. Consequently, there has been a substantial increase in the detector effective volume, as shown in Figure 5. The larger instrumented volume has increased the height of the plateau at high energies, whereas the new trigger increases the number of reconstructed events in the sub 10 GeV range by as much as a factor of two. Including these fainter, low-energy events has only had a minor effect on the angular resolution (see Figure 6).

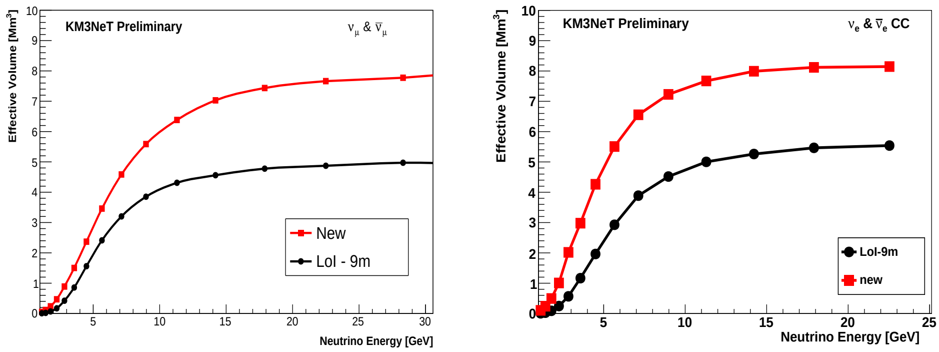

Figure 5: The change in ORCA effective volume after reconstruction, but before particle ID, for the muon (left) and electron (right) channels.

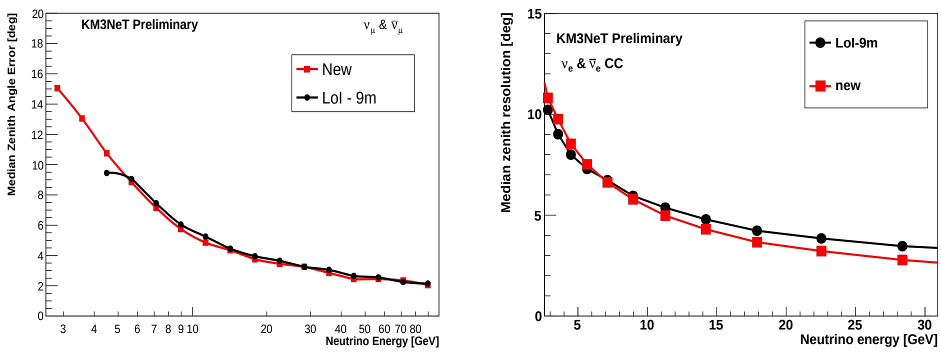

Figure 6: The corresponding change in zenith resolution after reconstruction, but before particle ID, for the muon (left) and electron (right) channels.

A new NMH sensitivity study is underway. However, this intermediate result is a cause for some optimism as the increase in effective volume is likely to lead to a corresponding increase in sensitivity.

References

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