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Status and physics results of the KM3NeT experiment

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Summary. — The KM3NeT submarine telescopes, currently under construction in the depths of the Mediterranean Sea, will enable the study of the Universe using neutrinos, the most elusive subatomic particles, as probe to investigate the depths of the Cosmos. KM3NeT-ARCA will study galactic and extra-galactic sources of very high energy neutrinos, thus operating in the field of the so-called "multi-messenger astronomy". The detection of neutrinos from an astrophysical source can provide important information on the emission mechanisms of these objects. KM3NeT-ORCA will instead deal with a basic physics study: the mass hierarchy of neutrinos. This contribution will describe the components of the two detectors and the first measurements carried out. In addition, the sensitivities of KM3NeT for several fundamental measurements will be described, such as cosmic neutrino fluxes from diffuse and point-like astrophysical sources and neutrino mass ordering.

1. – Introduction

Neutrinos have several properties that make them excellent messengers for the study of the Universe. Neutrinos are stable particles, so they can travel cosmological distances to reach Earth from the depths of the Universe, and they are neutral, so they are not deflected by electromagnetic fields in their path, retaining information about the region where they were produced, unlike charged particles. Their weak interaction also reduces their absorption by dense matter, making it possible to investigate the interior of the celestial objects that produce them. Finally, neutrinos constitute a "smoking gun" signature of the presence of hadronic processes in the mechanisms of gamma-ray production from astrophysical sources.

For all these reasons, large neutrino telescopes have been built to detect these particularly elusive messengers. Neutrino telescopes have access to energy ranges from MeV to PeV. At low energies, neutrinos produced by supernova explosions can be detected, while at energies of the order of the GeV, neutrino oscillations, mass ordering or the

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presence of sterile neutrinos can be studied. At higher energies, more exotic phenomena such as dark matter or magnetic monopoles can be studied, and at very high energies the window on neutrino astronomy is open, investigating the origin of cosmic rays and gamma rays of very high energy.

The international KM3NeT (Cubic Kilometre Neutrino Telescope) collaboration is building what is already the world's largest undersea neutrino telescope. The experiment involves two different sites in the Mediterranean Sea where two detectors with complementary scientific objectives are being built: KM3NeT-ARCA (Astroparticle Research with Cosmics In the Abyss) at 3500 m depth off the coast of Sicily and KM3NeT-ORCA (Oscillation Research with Cosmics In the Abyss) at 2500 m depth off the coast of Toulon (France). The location in the Mediterranean Sea provides an excellent view of the Galactic plane, making KM3NeT complementary to IceCube which is located at the South Pole.

In the next session the KM3NeT detector will be described, and then the main results obtained by KM3NeT-ARCA and KM3NeT-ORCA will be presented.

2. – The KM3NeT detectors

The KM3NeT telescope [1] will detect neutrinos by means of the Cherenkov light emitted by the particles produced by their interaction in the surroundings of the detector. For this reason, the detector consists of an array of photomultiplier tubes (PMTs) which are sensitive to single photons.

The photomultiplier tubes are arranged in Digital Optical Modules (DOMs) consisting of a pressure resistant glass sphere instrumented with 31 80 mm diameter PMTs in a three-dimensional arrangement. The DOMs are connected in groups of 18 to form vertical lines, called detection units (DUs). The DUs are anchored to the seabed and kept vertical by the buoyancy of the DOMs and by dedicated buoys located at the top. An array of 115 DUs forms a Building Block (BB). Each DU is connected to the seafloor infrastructure which provides the electrical power and optical data networks.

The two KM3NeT detectors share the same technology, adopting different instrumentation densities optimised for their respective primary physics goals. KM3NeT-ARCA will count two BBs, with a vertical spacing of 36 m between the DOMs and a 90 m horizontal distance between DUs, on average. The KM3NeT-ORCA single BB instruments a 7 Mton volume of seawater, having on average a 9 m vertical spacing between the DOMs and a 20 m horizontal distance between the DUs.

In the KM3NeT DOMs, the analog signals from the 31 PMTs are digitised by a custom front-end electronic board. The hit times of Cherenkov photons generating a signal above a threshold equivalent to 0.3 photoelectrons are digitised with nanosecond resolution. Following an all-data-to-shore concept, no data reduction is applied offshore. All hits are transmitted to a computing farm onshore where they are filtered and processed with trigger algorithms. The detectors are currently under construction, 7 DUs are taking data in the KM3NeT-ARCA site, while 9 DUs are taking data in the KM3NeT-ORCA site.

Several neutrino signatures are reconstructed in the detector depending on the flavour and interaction channel of the neutrino.The "golden" event channel in KM3NeT is the muon neutrino charged current interaction in which a long muon track traversing the detector is produced. This track direction can be reconstructed with sub-degree precision. The energy reconstruction is affected by the energy partially lost by the tracks not originating in the detector. The energy reconstruction of the neutrino event topologies

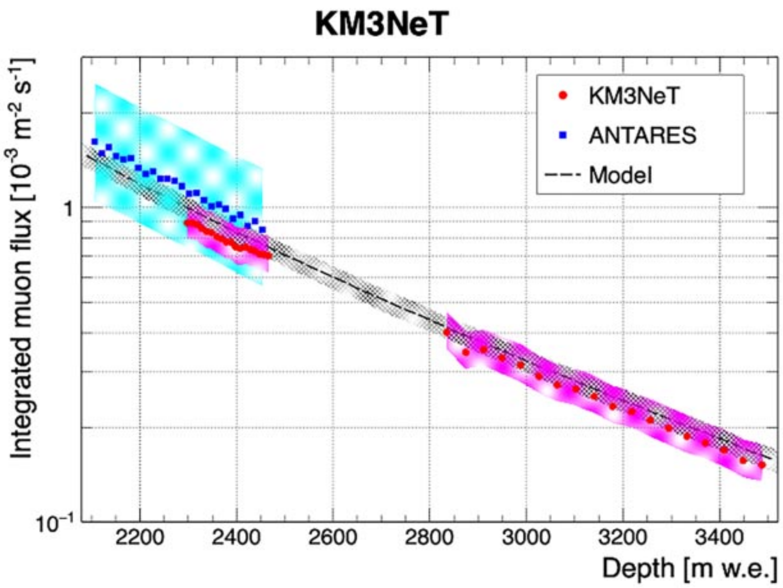

Fig. 1. – KM3NeT muon neutrino flux as a function of the depth compared with the ANTARES results and the calculation by Bugaev *et al.* [3].

with a dominant electromagnetic or hadronic shower is more precise especially once they are contained inside the detector. Thanks to the isotropic water properties the angular resolution for shower-like events is still better than a few degrees.

While both KM3NeT detectors are optimised to detect and study neutrinos, the dominant reconstructed events in both are in fact due to atmospheric muons. Created in cosmic ray interactions in the upper atmosphere, these atmospheric muons reach the KM3NeT detector at depths of 2-3 km below sea level only if they are initially highly energetic. So, such muons come from the most forward-boosted and early part of the cosmic-ray-induced air shower. Such muons are not able to cross the Earth so the common strategy to suppress this background is to look for events reconstructed as upgoing. The bulk of the events have a single muon. The ratio of the events with several muons is decreasing with increasing muon multiplicity. Nevertheless, the multi-muon events in neutrino telescopes represent one of the most critical backgrounds, strongly affecting systematic uncertainties due to the large theoretical uncertainty on their rates and their ability to mislead conventional single track event reconstructions bringing to wrong directions and/or unrealistically high energies.

The atmospheric neutrinos are produced in cosmic ray showers and they do not point to the cosmic source, so for the KM3NeT-ARCA detector they represent as background, irreducible with the upward selection. On the other end the KM3NeT-ORCA detector aims to determine the neutrino mass ordering by analysing the atmospheric neutrino distributions in energy and zenith angle.

The first lines of both detectors have already been used to measure the flux of atmospheric muons at different depths (fig. 1) [2]. The results are fully compatible with ANTARES, the KM3NeT predecessor, and the theoretical model by Bugaev *et al.* [3].

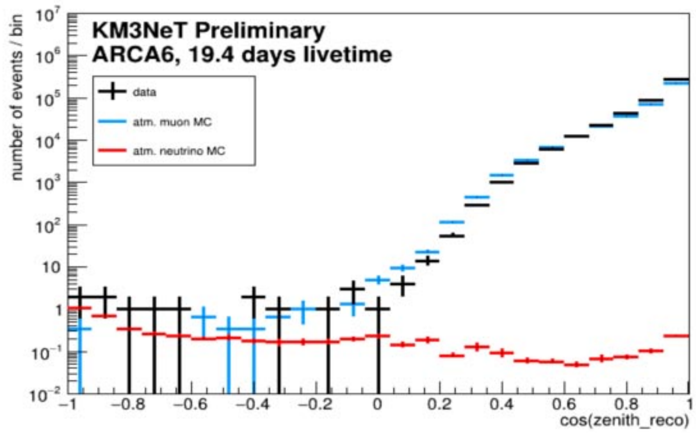

Fig. 2. – Comparison between the number of events reconstructed in 19.4 days by the first 6 DUs of KM3NeT-ARCA and the expected flux of atmospheric muons and neutrinos.

3. – KM3NeT-ARCA: first results and sensitivities

The first 6 DUs of the KM3NeT-ARCA detector have already allowed a preliminary measurement of the flux of muons and atmospheric neutrinos (fig. 2) [4].

The downgoing tracks are completely dominated by atmospheric muons, but by applying appropriate selection criteria and selecting the upgoing tracks, this background can be greatly suppressed. In particular, in this data sample, 15 upgoing tracks were selected in perfect agreement with the Monte Carlo prediction of 4 atmospheric neutrinos and 7 misreconstructed atmospheric muons. In any case, a good agreement between data and Monte Carlo simulation is found for both upgoing and downgoing tracks.

Two of the main objectives of KM3NeT-ARCA are the detection of point and diffuse neutrino sources. With respect to the latter, the aim is to detect the diffuse neutrino flux measured by IceCube [5]; the KM3NeT detector will be able to measure this diffuse cosmic neutrino flux in a very short time (fig. 3) [6]. The 5σ detection could be reached in just over a year.

The sensitivity of 2 BBs of KM3NeT-ARCA for point sources is shown in fig. 4 where the result is compared with other neutrino telescopes [7].

After 3 years of data taking, the two KM3NeT BBs will already have a sensitivity comparable to that of 7 years of IceCube data taking for positive declinations, while the sensitivity will be much better for negative declinations due to the better visibility of such region.

4. – KM3NeT-ORCA: first results and sensitivities

The first 6 DUs of KM3NeT-ORCA were already sufficient to make a first measurement of the neutrino oscillation (fig. 5) [8]. The data sample has a significance of no oscillations compared to oscillations hypothesis estimated at 5.9σ and correspondingly constrains on Δm^2_{31} and $sin^2\theta_{23}$ can be set (fig. 6) [8]. With only 6 DUs and almost one year of data, the result is in the same order of magnitude as competing experiments,

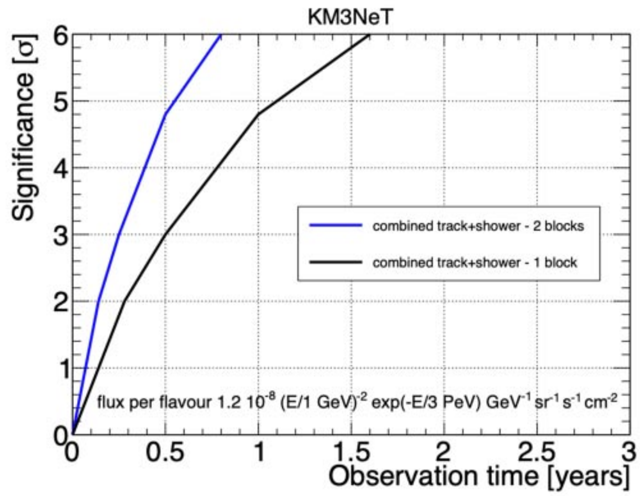

Fig. 3. – Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, for 1 BB (black line) and 2 BBs (blue line).

showing promise for future measurements with the KM3NeT-ORCA detector.

One of the main goal of KM3NeT-ORCA will be the determination of the neutrino mass ordering. The detector will be competitive with other experiments dedicated to this measurement, such as JUNO. Figure 7 shows the expected sensitivity to the mass hierarchy of the KM3NeT-ORCA BB as a function of the value of θ_{23} and of the type of ordering (direct or inverse) [10].

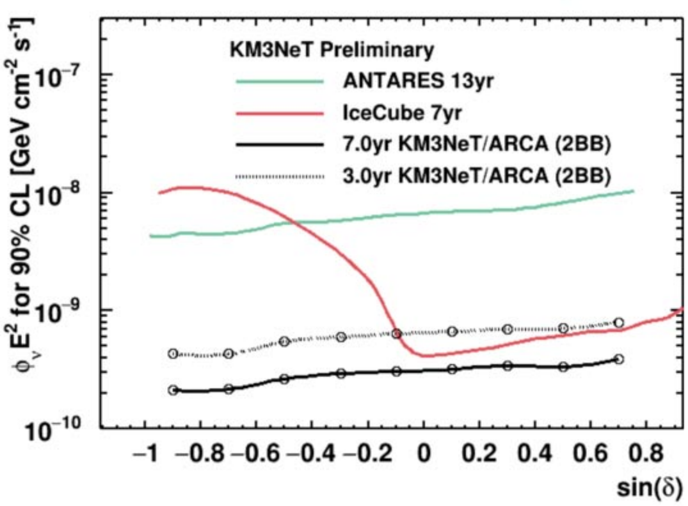

Fig. 4. – Flux normalisation for 90% CL limits to detect a E^{-2} point source with KM3NeT-ARCA compared with ANTARES (13 years) and IceCube (7 years).

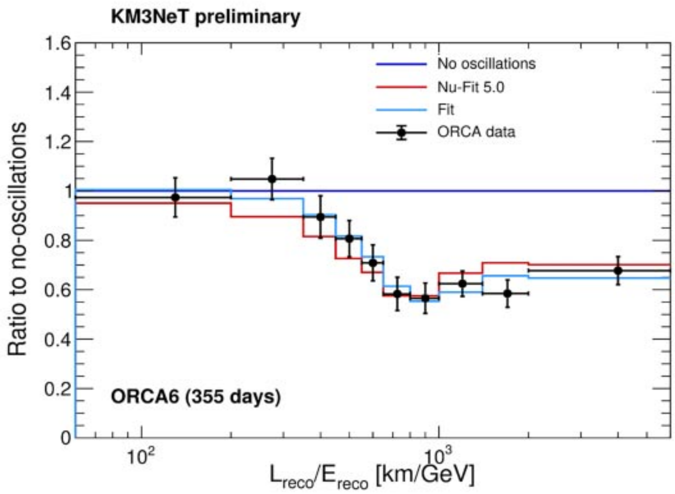

Fig. 5. – L/E distribution for the 6 DUs of KM3NeT-ORCA data and expected number of events relative to the "no oscillation" hypothesis. The no oscillations and NuFit [9] curves in this figure do not include systematic uncertainties.

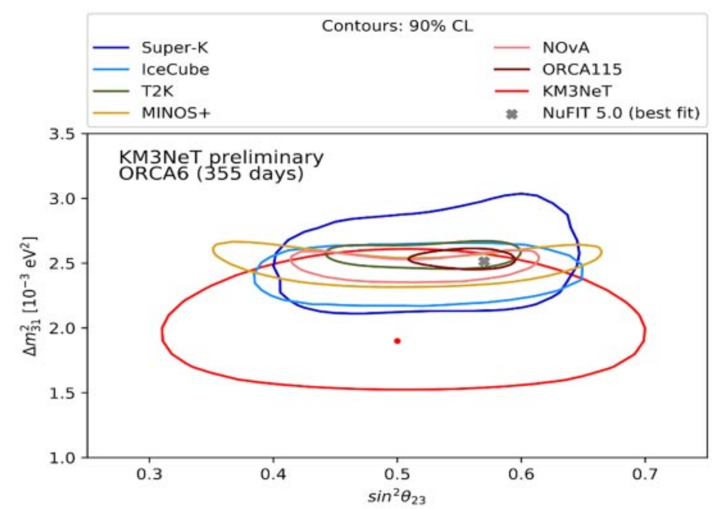

Fig. 6. – Contour at 90% CL of 6 DUs of KM3NeT-ORCA towards the oscillation parameters Δm^2_{31} and $sin^2\theta_{23}$. Contours of other experiments have been added for comparison purposes as well as the NuFit best fit value [9]. In particular the red line marked as "KM3NeT" refers to the result obtained with 6 DUs, while the brown line marked as "ORCA115" refers to the expected sensitivity of the full KM3NeT-ARCA BB.

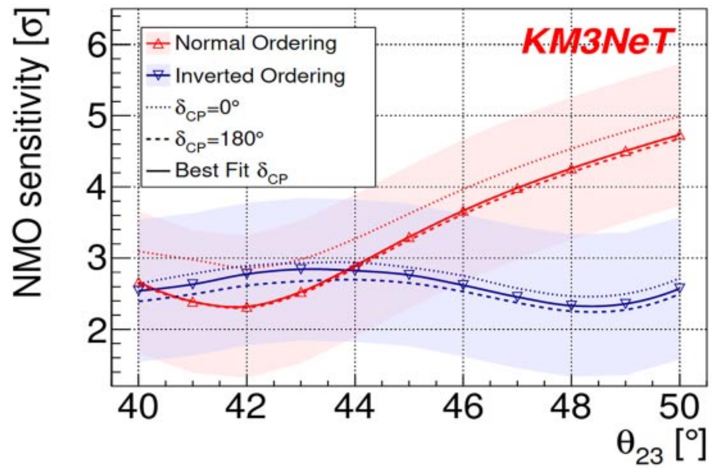

Fig. 7. – Sensitivity to neutrino mass ordering after 3 years of data taking, as a function of the true θ_{23} value, for both normal (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) under three assumptions for the δ_{CP} value. The coloured shaded areas represent the sensitivity that 68% of the experiment realisation would yield, according to the Asimov approach.

5. – Conclusions

KM3NeT will open a new window on the study of the Universe and the fundamental properties of the neutrino. The Collaboration will be able to study such diverse phenomena thanks to the complementarity of the KM3NeT-ORCA detector, which is dedicated to energies of the order of the GeV, and the KM3NeT-ARCA detector, which will focus on higher energies, up to and beyond PeV.

The technology implemented in the detectors is well established and all preliminary calibrations have shown the expected performance, both for the measurement of atmospheric muon and atmospheric neutrino fluxes. At present, 7 DUs of the KM3NeT-ARCA detector have been collecting data smoothly since September 2021, while 9 DUs of the KM3NeT-ORCA detector have been operational since November 2021.

The KM3NeT-ARCA telescope will become in the near future one of the main players in the neutrino astronomy panorama; at the moment its effective area is already larger than that of ANTARES, its predecessor. In particular, thanks to its geographical position, KM3NeT-ARCA has an excellent view of the galactic centre, making it complementary with IceCube, the first detector to have measured a diffuse flux of cosmic neutrinos and to have identified the supermassive black hole TXS 0506+056 as a possible source of cosmic neutrinos [11]. The full KM3NeT-ARCA detector will have comparable or better performance (depending on the declination of the sources) than IceCube, so it is expected to confirm the IceCube measurements and identify new sources of cosmic neutrinos in a few years of data taking. The KM3NeT-ORCA BB, dedicated to the measurement of atmospheric neutrinos, will have sufficient sensitivity to determine the mass ordering of neutrinos in less than 6 years in the worst scenario, making it competitive with other experiments such as JUNO. Several analysis presented in this contribution have been meanwhile updated and they have been presented at the Neutrino 2022 conference.

The deployment of additional DUs at both KM3NeT-ARCA and KM3NeT-ORCA sites is expected in 2022. The detector will reach completion in the coming years.

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