PROCEEDINGS OF SCIENCE

Sensitivity for astrophysical neutrino searches with KM3NeT-ORCA

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The KM3NeT facility, the next generation of large neutrino detectors, is currently being deployed in the Mediterranean Sea. KM3NeT will consist of two ARCA ("Astroparticle Research with Cosmics in the Abyss") building blocks, optimized for very high-energy astrophysical neutrinos, and of the ORCA one ("Oscillation Research with Cosmics in the Abyss"). While ORCA has originally been designed to study neutrino oscillations using atmospheric neutrinos, this dense array may also be used for astrophysical neutrino searches. We present a first estimate of the sensitivity for GeV–100GeV neutrino searches in time/space coincidence with GW alerts sent by the LIGO and Virgo collaborations (LVC). We use the final configuration of ORCA, i.e. ORCA-115 detection units, to estimate the sensitivity of ORCA to gravitational wave events that may be detected by LVC during O3.

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36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

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1. Motivation for low-energy astrophysical neutrino searches

Large neutrino telescopes, such as ANTARES [1] and IceCube [2], have so far focused on detecting astrophysical neutrinos in the TeV–PeV energy range. The community searches for point source [3] or diffuse emissions [4], and uses the framework of multi-messenger astronomy to search for neutrino counterparts to transient phenomena detected via gravitational or electromagnetic waves. The GeV energy range, characterized by a more intense atmospheric neutrino flux, is usually dedicated to neutrino physics, for instance, mixing angle or neutrino mass ordering studies [5].

In these proceedings, we assess the capability of KM3NeT/ORCA [6] to carry out astrophysical neutrino searches in the 1-100 GeV range. These studies are motivated by the complementary processes that may generate GeV and $\geq$ TeV neutrinos. As an example, we can consider the case of gamma-ray bursts: a TeV neutrino emission is expected to be produced by the internal shock in the prompt emission phase [7], while GeV neutrinos are thought be produced by collisions of neutrons and protons following their decoupling during the acceleration phase [8] or by interactions of the accelerated proton flux with a dense environment surrounding the source [9]. GeV neutrino searches could therefore lead to the evidence of hadronic acceleration mechanisms but also constitute a probe of the amount of matter surrounding the astrophysical object. This allows one to better constrain the environments, acceleration processes, and progenitors of these phenomena.

Until recently, the Super-Kamiokande (SK) detector, optimized for neutrinos in the MeV–GeV range, was the only neutrino detector in operation able to provide limits on the astrophysical neutrino flux in the GeV regime. It has set, among others, limits from the recent binary neutron star merger GW170817 [10]. The IceCube Neutrino Telescope [2], and in particular its low-energy, denser infill detector DeepCore (DC), offered up to now the only attractive alternative to study the GeV range [11]. Unfortunately, the large photosensors of IceCube-DC, originally optimized to search for neutrinos with energies above 10 GeV, are rather distant from each other. As a consequence, efficient detection and directional reconstruction are therefore challenging for GeV neutrino interactions. The most appealing alternative to overcome both volume limitations of SK and sensitivity limitations of IceCube is KM3NeT/ORCA.

2. Description of KM3NeT and the *NMO* selection

ORCA (Oscillation Research with Cosmics in the Abyss) is the low-energy branch of the KM3NeT project [6]. It will consist of a multi-megaton deep-sea detector optimized for the detection of neutrinos in the 1-100 GeV range and mainly targets fundamental neutrino physics, in particular the measurement of the neutrino mass ordering (NMO) with atmospheric neutrinos [5]. The ORCA digital optical modules (DOMs) rely on the innovative KM3NeT design featuring 31 small (3-inch) photosensors in one glass sphere [6]. Such DOMs provide increased performance in photon counting, directionality and background rejection, leading to better selection and reconstruction capabilities for neutrino events. The first ORCA detection unit (DU), a flexible line about 200 m high and supporting 18 DOMs equally spaced by 9 m, has been installed in September 2017 off the shore of Toulon (France); currently 4 DUs are taking data in the ORCA site. Over the next years, ORCA is expected to become a 6 Mt detector (115 DUs with a typical spacing of 20 m in average). ORCA will thus soon have an instrumented volume 100 times larger than SK and a density of photosensors about 30 times higher than IceCube-DC.

Event selection and reconstruction capabilities have already been extensively studied in the 1-100 GeV range for the studies of the neutrino mass ordering [5].

3. Use of the NMO selection in astrophysics

The starting point of this analysis is the event pre-selection optimized for the NMO analysis [5]. To this end, events are required to (a) pass a pre-selection based on reconstruction quality, (b) have a reconstructed vertex contained inside or close to the instrumented volume, and (c) be reconstructed as upward traveling in the detector. This pre-selection ensures good reconstruction performance (a, b) and suppresses already part of the dominant backgrounds (b, c) caused by atmospheric muons and pure noise events induced by radioactive decays of ^{40}K and light-emitting organisms. Although the optical background varies with location in the detector and in time, in the simulations, a constant 10 kHz overall noise rate per PMT and higher-fold coincidences on DOMs are taken into account.

With this already-established selection of neutrinos, the selected sample has a median angular reconstruction precision within 20 degrees at low energies and lower than 5 degrees at 100 GeV, allowing some astrophysical searches to be carried out.

Since after pre-selection the remaining background still exceeds the atmospheric neutrino flux by more than two orders of magnitude, the events are passed through a random forest classifier. The output results are 3 different scores, with values between 0 and 1:

- A track-score used to differentiate track-like (arising from charged current interactions of the ν_μ) from shower-like events (all flavors but mainly ν_e interactions). By default, an event is defined as a track (shower) if its track-score is $\geq(<)$ 0.6.
- A muon-score, dedicated to tag atmospheric muon candidates. The default criteria requires a score $\leq$ 0.05 in the NMO analysis.
- A noise-score, which helps reducing the pure noise event contamination in the final sample. The default value used in the NMO analysis is $\leq$ 0.1.

In view of using this event selection for astrophysical searches, we have optimized the muon-score and noise-score for maximizing the signal-to-noise ratio ($S/\sqrt{(S+B)}$). In this expression, Signal (S) represents the sum of neutrino events being either reconstructed and pre-selected by the shower-reconstruction algorithm with a track-score smaller ($<$) than 0.6 or being reconstructed and pre-selected by the track-reconstruction algorithm as track with a track-score larger ($\geq$) than 0.6. A spectral index of -2 was assumed between 1 and 100 GeV, with a normalization of the flux such that 3 signal events can be detected in KM3NeT. The background (B) is here defined as the sum of atmospheric neutrinos, atmospheric muons and pure noise events passing the above-described event selection. The events that pass none of the above conditions are not considered in the final sample. Fig. 1 shows the result of the optimization, where both the noise-score and the muon-score cuts could take values between 0.05 and 1 with an increment of 0.1. The values that maximize the signal-to-noise ratio are muon-score $\leq$ 0.15 and noise-score $\leq$ 0.15.

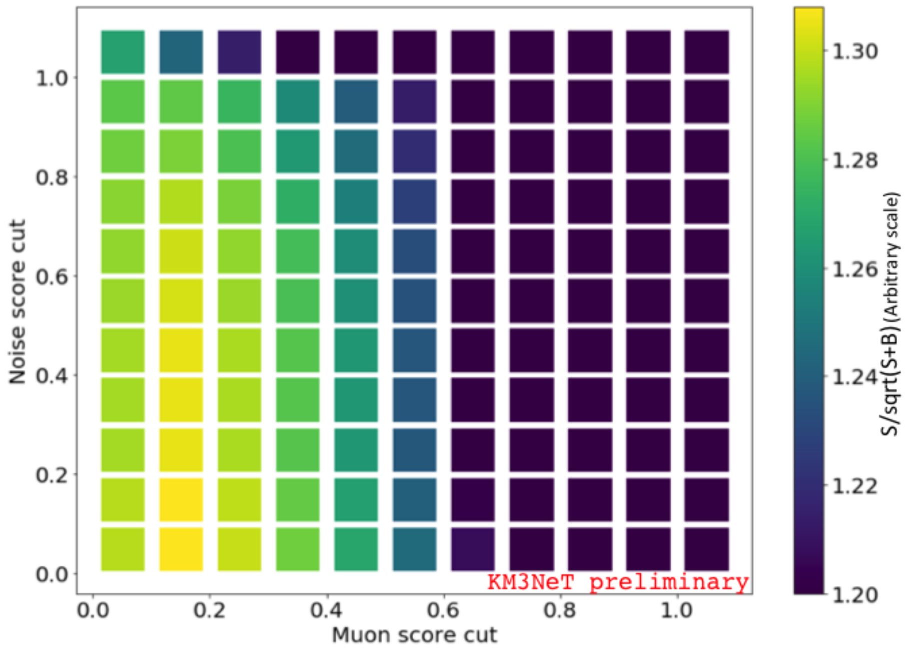

Figure 1: Result of the optimization of the noise-score and muon-score in view of maximizing the signal-to-noise ratio for astrophysical searches. The minimum of the color scale has been set to highlight the region of interest.

Once the criteria on the noise-score and muon-score are applied, the final rate of the event selection is estimated to be 0.004 Hz. This value will be re-evaluated once a larger detector will be operating and data–simulation comparison will be carried out. Considering the potentially large variation in the noise rate due to the changing environment, as previously described, the exact rate will be computed for each event independently using a data-driven approach.

The effective area corresponding to this selection as function of the true energy is shown in Fig. 2. For comparison, Fig. 2 also shows the effective area for point source searches in ANTARES [12] and the point source and Gamma-Ray Follow-up samples in IceCube [13]. Note that the work presented in these proceedings aimed at evaluating the potential of the NMO selection when the final level is optimized for astrophysical searches. A detailed optimization of every step of the event selection will be carried out in the near future, and the effective area presented here should thus be considered as a conservative estimate of ORCA capabilities. As shown in Fig. 2, a reduced version of ORCA, e.g. ORCA 7 DUs in the figure representing an exemplary intermediate configuration during construction, will already allow us to be competitive with existing analyses in the considered energy range.

4. Example of application: probing neutrino emission from binary compact mergers

We can use the event selection previously described to search for a neutrino counterpart to compact binary mergers detected by the LIGO and Virgo (LVC) interferometers [14]. Similarly to

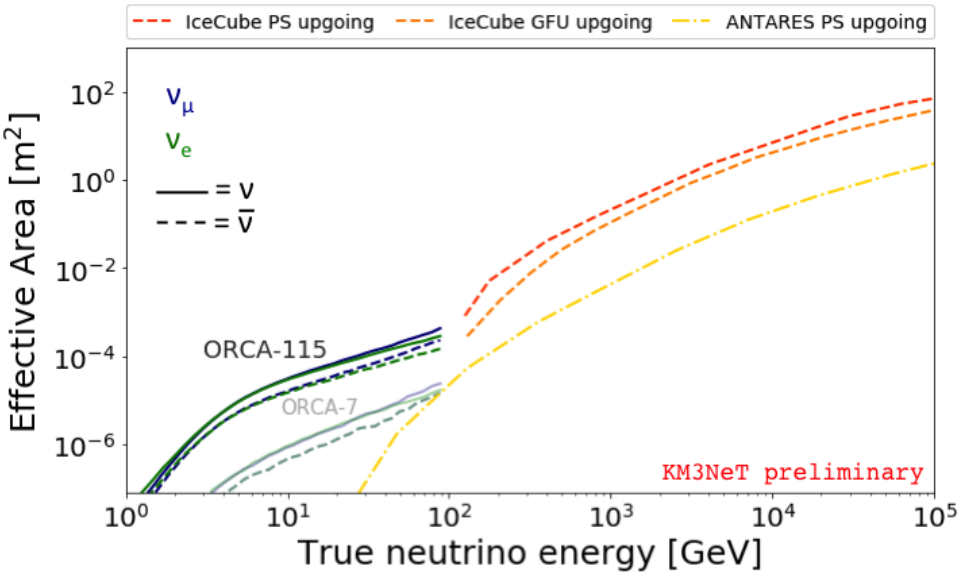

Figure 2: Effective area as function of the energy for low-energy neutrinos when applying the NMO selection described in these proceedings to KM3NeT/ORCA data. The ORCA effective area is compared with the effective area for high-energy neutrino searches in other neutrino detectors: ANTARES point source (yellow line), IceCube point source (red line) and IceCube GFU (orange line).

what was performed in [15], a conservative time window of [t–500s, t+500s] (where t is the merger time reported by LVC) [16] is used in this analysis. The analysis method is based on a neutrino event counting experiment in this time window.

We estimate the 90% sensitivity level of the analysis by searching for a significant deviation from the Poissonian background distribution integrated over 1000 s. Three signal events are needed to reach the sensitivity level, and this leads to a sensitivity on the neutrino fluence of 3×10^5 GeV m^{-2}.

The sensitivity level on the flux can be converted into a limit on the isotropic-equivalent energy E_{iso} released by the astrophysical event. This variable allows for comparison with constraints set using other messengers such as gamma-rays or gravitational waves. The sensitivity on E_{iso} for GW170817 is shown together with constraints set with high-energy neutrinos [15] or with Super-Kamiokande [10], and the detection made by Fermi-GBM. As it can be seen in Fig. 3, KM3NeT/ORCA will be able to produce competitive constraints compared to existing neutrino searches, in an energy range that has been poorly studied so far.

5. Summary and Perspectives

In these proceedings, we have discussed the possible use of the event selection originally

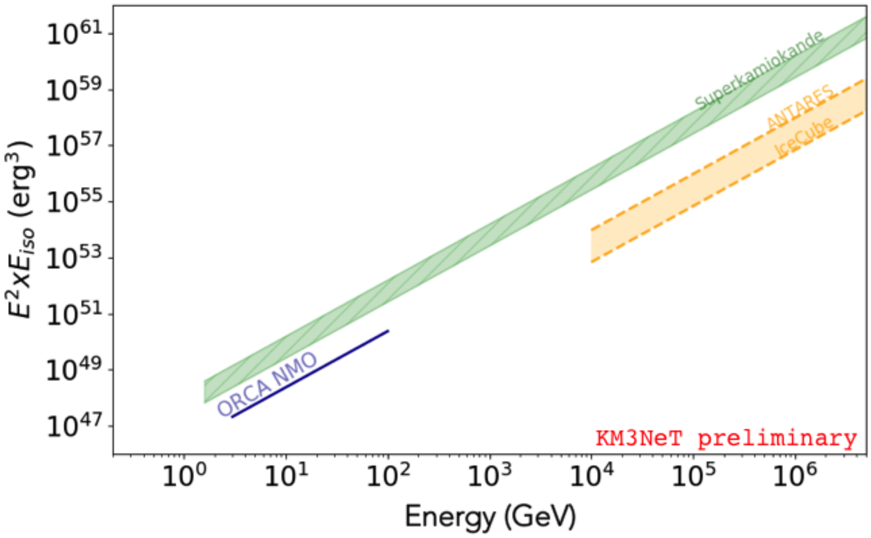

Figure 3: Comparison of $E^2 \times E_{iso}$ constraints for the neutrino search presented in this work with the searches performed by Super-Kamiokande and using high-energy neutrinos. A time window of 1000 s was used for the presented work, similarly to what was used to obtain the constraints using high-energy neutrinos or Super-Kamiokande data. We assumed the source was placed in an ideal position for ORCA, i.e. leading to upgoing events, while GW170817 was placed in the opposite position for ANTARES.

dedicated to mass-hierarchy determination in KM3NeT/ORCA for astrophysical neutrino searches. The parameter selection has been optimized based on the current estimate of the background and could derive the expected effective area in the 1–100 GeV energy range. As an example, we have applied this event selection to an event similar to GW170817 but ideally placed for ORCA. For comparison, we have shown the expected sensitivity of KM3NeT/ORCA with the constraints set by Super-Kamiokande and the high-energy neutrino searches performed by the ANTARES and IceCube collaborations. The combination of KM3NeT/ORCA and the other running experiments will therefore allows one to constrain the neutrino spectrum, and thus the different processes that may produce a neutrino flux, over a large energy range.

In the coming years, the fraction of ORCA that is deployed and taking data will continuously increase and will allow us to start probing GeV neutrino emission from transient phenomena. While the example of compact binary mergers was considered in these proceedings, we note that similar analyses may be applied to other transients, such as solar flares [17], gamma-ray novae [18], or fast radio bursts [19]. Dedicated analyses for each of these transients will be developed in the coming months.

PoS(ICRC2019)934

Acknowledgments

This project has received funding from Region Ile-de-France (DIM-ACAV, LEANOR project), Agence Nationale de la Recherche (contract ANR-15-CE31-0020), the European Union's Horizon 2020 research and innovation programme under grant agreement No 653477.

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PoS(ICRC2019)934