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The KM3NeT online analysis system

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KM3NeT is a multi-purpose neutrino detector under construction in the Mediterranean Sea and currently taking data with a partial detector configuration. It is composed of two deep-sea water-Cherenkov detectors located at two different sites: ARCA (Italy), optimised for the detection of high-energy cosmic neutrinos in the TeV-PeV range, and ORCA (France), optimised for low-energy atmospheric neutrinos in the few-GeV range. Thanks to the multi-PMT design of their optical modules, both detectors are sensitive also to MeV neutrinos emitted by core-collapse supernovae, allowing them to be used for neutrino astronomy across an energy range from a few MeV to a few PeV. KM3NeT is actively involved in real-time multi-messenger searches, which aim at studying transient astrophysical phenomena by the simultaneous observation of different cosmic messengers. Given their large field of view and almost 100% duty cycle, neutrino telescopes are ideally suited to early notify other multi-messenger facilities when interesting neutrino candidates are detected and to perform follow-ups of external triggers. To achieve these goals, the KM3NeT Collaboration has set up an online analysis platform that continuously performs real-time reconstruction and classification of all ARCA and ORCA events, core-collapse supernova searches, and follow-ups of received alerts. This contribution reports about the current status of the KM3NeT online analysis system.

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1. Introduction

The discovery of high-energy astrophysical neutrinos by the IceCube Neutrino Observatory [1] marked the beginning of a new era in neutrino astronomy and multi-messenger astrophysics. Electrically neutral and weakly interacting, neutrinos are unique messengers that can escape dense astrophysical environments and travel cosmological distances without being deflected or absorbed. As such, they play an important role in the identification and study of transient astrophysical sources, especially in the context of real-time multi-messenger campaigns triggered by or in response to external alerts. Neutrino telescopes can leverage their wide field of view and nearly continuous operation to provide prompt notifications to other multi-messenger observatories and to perform follow-up searches in spatial and temporal coincidence with external alerts. In this context, the KM3NeT Collaboration has developed an online analysis system aiming at processing events as soon as they are collected and launching automatic multi-messenger searches. The design and performance of the KM3NeT online analysis system are presented in this contribution, while the results of the KM3NeT online analysis and the current status of the KM3NeT alert system are reported in [2] and [3], respectively.

2. KM3NeT

KM3NeT [4] is a next-generation deep-sea neutrino telescope under construction in the Mediterranean Sea. It consists of two detectors located at different sites, sharing the same technology but designed to address different physics goals. Each detector is configured in a three-dimensional array of Digital Optical Modules (DOMs) [5], mounted on vertical Detection Units (DUs) anchored to the seabed and kept vertical by buoyancy. A DU comprises 18 DOMs, each containing 31 photomultipliers (PMTs) designed to detect the Cherenkov light produced by relativistic charged particles emerging from neutrino interactions. The ARCA detector is located 100 km offshore from Portopalo di Capo Passero, Sicily, Italy at a depth of 3500 m. It is optimised for the detection of cosmic neutrinos in the TeV-PeV energy range, with a horizontal spacing of 90 m between DUs and a vertical spacing of 36 m between DOMs. The ORCA detector is situated 40 km offshore from Toulon, France, at a depth of 2450 m. ORCA is optimised for the detection of low-energy atmospheric neutrinos, with a horizontal spacing of 20 m between DUs and a vertical spacing of 9 m between DOMs. Thanks to the multi-PMT design of their optical modules, both ARCA and ORCA are sensitive also to $\sim$10 MeV neutrinos from Core-Collapse Supernovae (CCSNe), which can be detected by searching for coincident PMT signals in single DOMs exceeding the background level.

When completed, KM3NeT will consist of two building blocks for ARCA and one for ORCA, each containing 115 DUs, and will include more than 6200 DOMs and approximately 200000 PMTs. Although still under construction, KM3NeT is already taking data in a partial detector configuration. Results presented here refer to ARCA28 (28 DUs) and ORCA24 (24 DUs).

3. The KM3NeT online analysis system

Once collected, data are sent from each detector to the corresponding control station on shore following an *all-data-to-shore* approach. There, they are filtered by the Data Acquisition (DAQ)

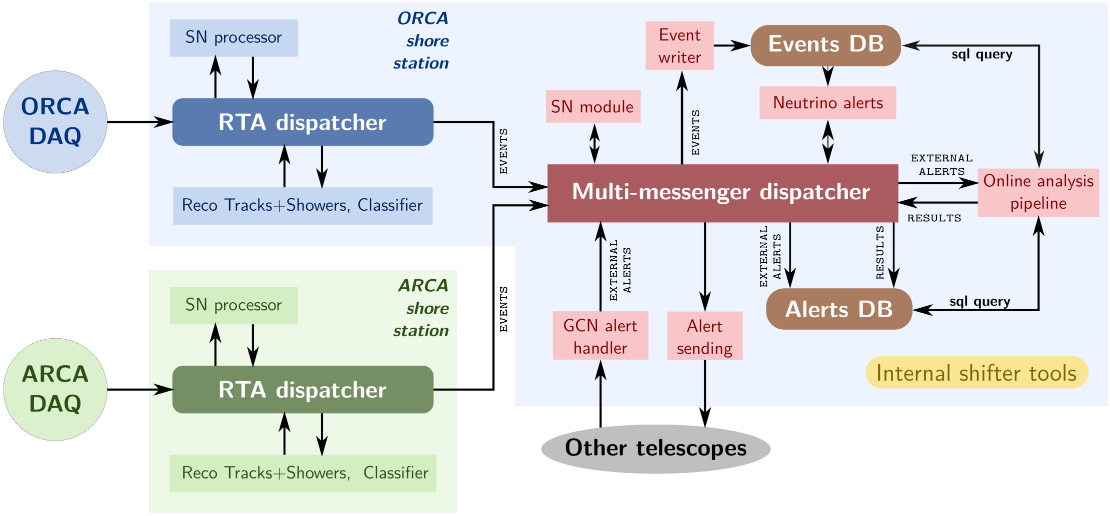


Figure 1: Schematic overview of the KM3NeT online analysis system.

system and then mirrored to the KM3NeT online analysis system, schematically represented in Fig. 1. At each shore station, a Real-Time Analysis (RTA) dispatcher continuously sends data to two modules: a MeV module, aimed at searching for MeV neutrinos from CCSNe, and a GeV-PeV module, dedicated to the multi-core reconstruction and classification of triggered events. After being processed, data are sent to a common multi-messenger dispatcher and made available for follow-up searches of external triggers and identification of interesting neutrino events.

3.1 The MeV CCSN processing

The main detection channel of CCSN MeV neutrinos for KM3NeT is the inverse beta decay of $\overline{\nu}_e$ on free protons in water, which produces a positron travelling a short distance compared to the KM3NeT DOM spacing. Since the KM3NeT configuration is optimised for neutrino energies above the GeV scale, the Cherenkov signatures from MeV neutrinos are too localised to be individually reconstructed. The detection of CCSN neutrinos in KM3NeT is based on the observation of an excess of coincidences between PMTs in single DOMs above the expected background, so that each individual DOM acts as a standalone detector [6]. The main sources of background for this search are bioluminescence, radioactive decays and atmospheric muons. In order to enhance the ability to discriminate between CCSN neutrinos and background, the CCSN search makes use of the *multiplicity* defined as the number of unique PMTs involved in a coincidence within a 10 ns window. Bioluminescence emission is negligible for multiplicities above 2, while radioactive decays dominate in the low multiplicity region extending up to a value of 7. The contribution from atmospheric muons, which dominates at multiplicities of 8 and above, can be reduced by exploiting the fact that muon tracks typically produce correlated coincidences across multiple DOMs. In this context, a CCSN event is defined as a coincidence on a DOM that satisfies the optimal selection criteria based on the previous considerations. The MeV CCSN module running at each shore station (SN processor in Fig. 1), takes the raw PMT data as input and computes, every 100 ms, the number of CCSN events in a 500 ms sliding window, which corresponds to the typical duration of the

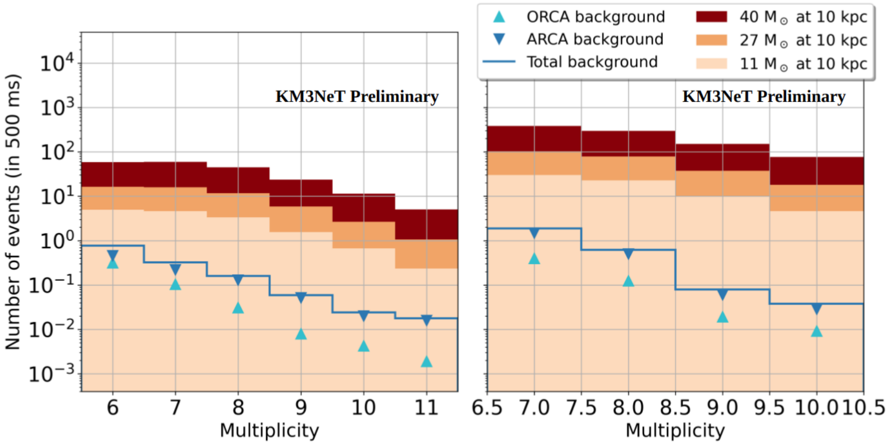
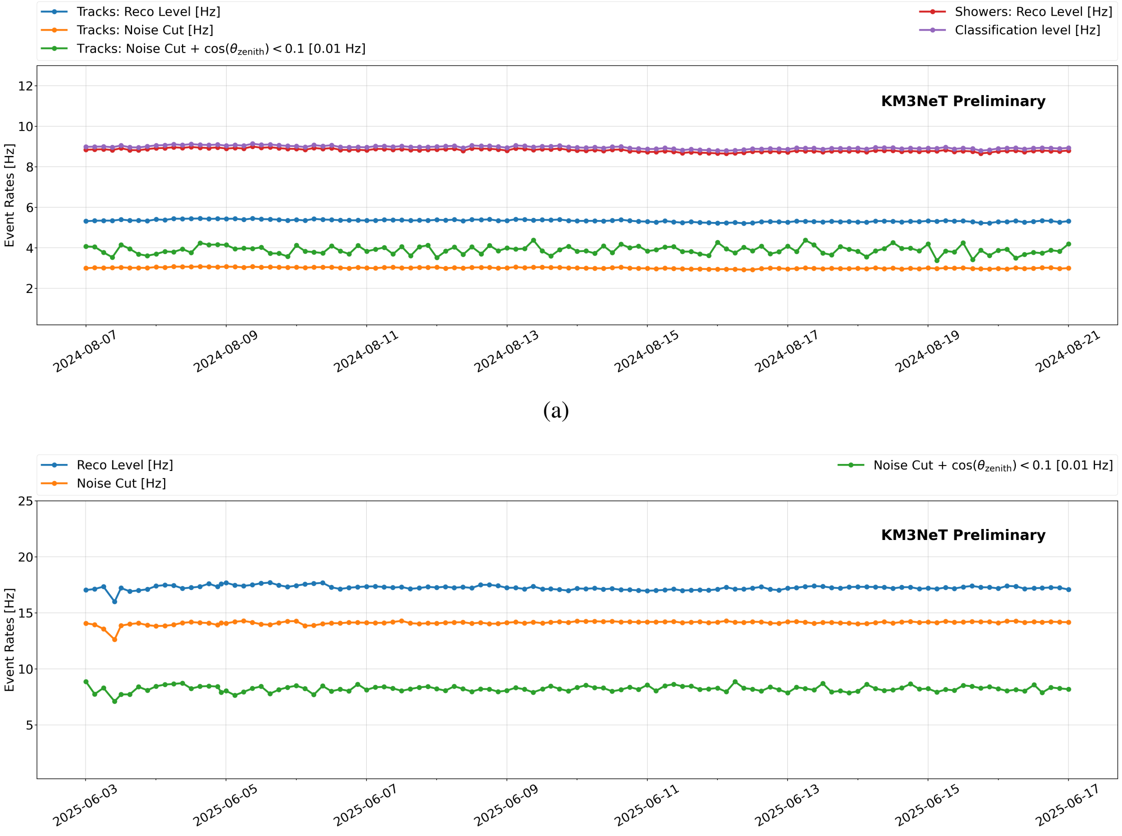


Figure 2: Expected number of CCSN events from supernova progenitors with different masses and estimated backgrounds as a function of the multiplicity for ARCA29-ORCA24 (left) and ARCA230-ORCA115 (right), after selection cuts. Figure from [10].

accretion phase of the $\overline{\nu}_e$ burst [7, 8]. Data are then sent to the common multi-messenger dispatcher and used to evaluate a combined significance aimed at identifying a CCSN. KM3NeT is currently able to send alerts to SNEWS [9] with a latency lower than 20 s and a false alarm rate less than 1/week. Additionally, a triggered analysis pipeline allows KM3NeT to perform follow-up searches for MeV neutrinos in coincidence with external alerts. The expected number of CCSN events from 11 M$_\odot$, 27 M$_\odot$ and 40 M$_\odot$ supernova progenitors in a 500 ms time window as a function of the multiplicity, for the detector configurations ARCA29-ORCA24 and ARCA230-ORCA115, is shown in Fig. 2, together with the estimated backgrounds. Signal and background distributions are those obtained after selection cuts with the new search approach described in [10]. For a progenitor's mass of 11 M$_\odot$ or above, KM3NeT will achieve full galactic sensitivity when completed [10].

3.2 The GeV-PeV processing

Neutrinos in the GeV-PeV energy range can trigger multiple DOMs and produce two different topological signatures: track-like and shower-like events. Track-like events result from muons produced in ν_μ charged current (CC) interactions and ν_τ CC interactions when the τ decays into a muon. Thanks to the long distances they can travel within the detector, muons produce a narrow and straight signal, leading this class of events to be characterised by a good angular resolution. Shower-like events, on the other hand, originate from all-flavour neutral current (NC) interactions, ν_e CC interactions and ν_τ CC interactions when the τ decays into an electron or hadrons. In this case, the energy is deposited within a few meters from the interaction vertex, resulting in a better energy resolution but a worse angular resolution compared to track-like events. For reference, the ARCA28 median angular resolution is below 0.1° above 1 PeV for track-like events, and approximately 2° around 100 TeV for shower-like events [11]. In order to account for these two event topologies, the GeV-PeV processing module at each shore station continuously reconstructs events both as tracks and showers using two dedicated algorithms [12]. The reconstruction algorithms used in the GeV-PeV online processing module are the same as those adopted in the offline reconstruction, but, unlike the latter, they rely on preliminary information on detector positioning, orientation and



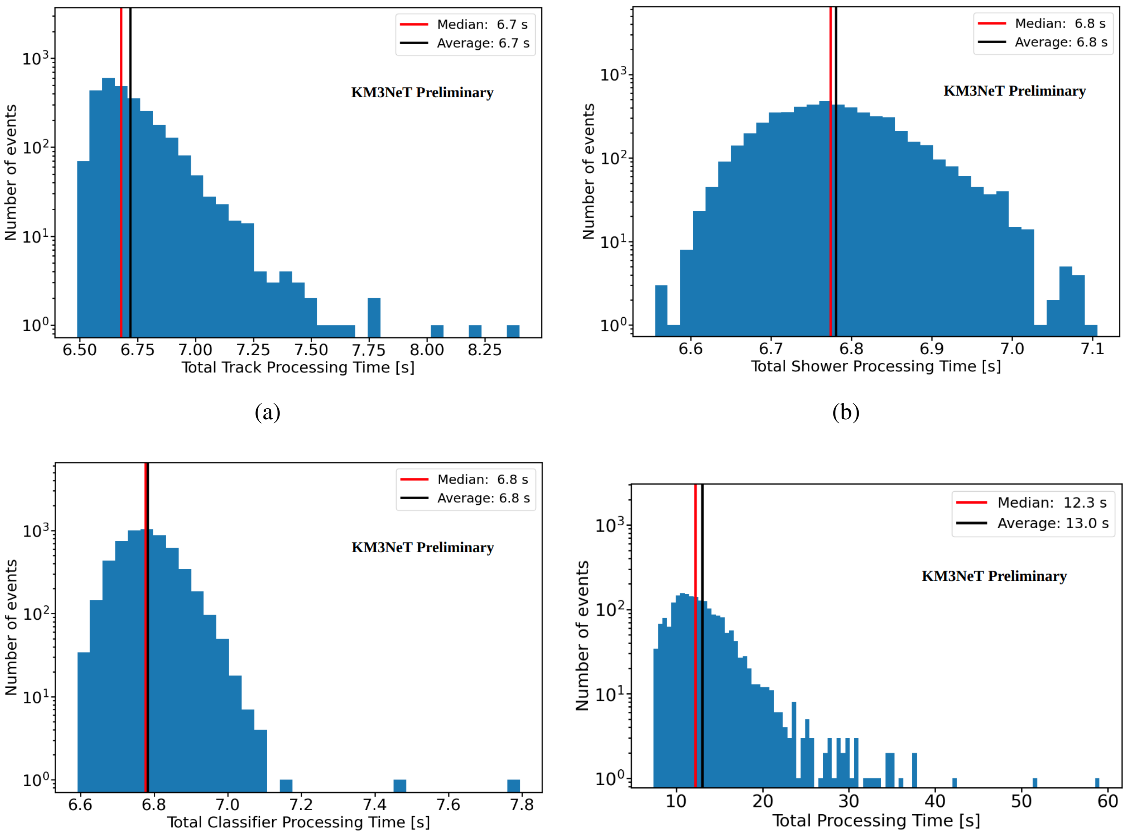
(a)

(b)

Figure 3: Rate of reconstructed and classified events as a function of time for ARCA28 (a) and ORCA24 (b), over a two-week period. For ARCA, the rates at track reconstruction level (blue line), shower reconstruction level (red line) and classification level (purple line) differ due to the parallelised implementation. For ORCA, the single rate at reconstruction level (blue line) reflects the sequential application of track reconstruction, shower reconstruction and classification. For both ARCA and ORCA, the event rates after noise cut i.e. by requiring a minimum number of PMT hits in each event (orange line) and after applying both noise cut and track upgoing selection (green line) are also shown.

timing, since dynamic calibrations are not yet implemented at the online processing level. Machine learning techniques are also integrated into the module to separate neutrinos from the atmospheric muon background.

The architecture of the GeV-PeV processing module differs between ARCA and ORCA: in ARCA, track reconstruction, shower reconstruction, and classification are parallelised, while in ORCA they are executed in series. ARCA event classification is based on a Graph Neural Network (GNN) that operates independently of reconstruction outputs [13], allowing it to be run in parallel with reconstruction. ORCA classification, on the other hand, relies on a Boosted Decision Tree (BDT) that takes the reconstruction results as input, requiring it to be applied after reconstruction. In order to handle the high rate of triggered events with low latency, multi-core processing is in place for both ARCA and ORCA. The rate of reconstructed and classified events from the GeV-PeV processing module for ARCA28 and ORCA24 over a two-week period is shown in Fig. 3. As a



(a) (b)

(c) (d)

Figure 4: Total processing time distributions for ARCA28 track reconstruction (a), shower reconstruction (b) and classification (c), and ORCA24 sequential application of track reconstruction, shower reconstruction and classification (d). The total time required to process an event is computed with respect to its trigger time, and thus also accounts for data filtering, buffering and dispatching.

result of the ARCA28 parallelised processing, events are reconstructed and classified in a median time of ~6.8 s after they are triggered, as shown in Fig. 4(a), 4(b) and 4(c). In comparison, the ORCA24 serial implementation allows for processing events with a median delay of ~12.3 s, as shown in Fig. 4(d). These latencies include the time required for data filtering from background noise, buffering and dispatching, as well as for event reconstruction/classification. For each event, the total processing time is dominated by the former, which has a median value of approximately 6.5 s for ARCA28 and 7.5 s for ORCA24, while the contribution from the latter is ~0.3 s for each ARCA28 parallelised process and ~4.8 s for the ORCA24 sequential processing.

3.3 The common multi-messenger modules

As shown in Fig. 1, the common multi-messenger dispatcher enables communication between different multi-messenger modules hosted at the ORCA shore station. These modules take care of event storage, external alert reception, follow-up analyses, selection of interesting neutrino events, CCSN final processing, results storage and alert sending. As soon as events are processed by the

GeV-PeV processing module, they are sent to the common multi-messenger dispatcher and stored in a local event database, making them available for identification of interesting neutrino candidates [3] and follow-up searches automatically triggered by external alerts. Several follow-up analyses are currently implemented, searching for KM3NeT events in spatial and temporal coincidence with Gravitational Waves (GWs), Gamma-Ray Bursts (GRBs), IceCube neutrinos, Fast Radio Bursts (FRBs), microquasars, general transients and CCSNe, as detailed in [2]. Since these analyses are performed considering different time windows defined around the time of the alert, storing events in a local database ensures their availability when needed. For the CCSN search, the outputs from the ARCA and ORCA SN processors are sent to a common SN module, aimed at performing both CCSN final processing and follow-up analyses for MeV neutrinos, as described in Sect. 3.1. Once the results from the different modules are available, they are sent to the multi-messenger dispatcher and stored in an alert database together with received alerts. Results from follow-up searches can be visualised through an internal web application called *Shifter Tools*, which also includes monitoring pages used to continuously check the stability of the system, with the support of dedicated shift crews. The KM3NeT online analysis system has been systematically performing follow-up analyses of external alerts since June 2023, while the public distribution of alerts when interesting neutrino events are detected is expected to start before the end of this year.

4. Conclusions

KM3NeT consists of two deep-sea neutrino telescopes, namely ARCA and ORCA, currently under construction but already taking data in partial detector configurations. In order to actively participate in real-time multi-messenger searches, KM3NeT implements an online analysis system aimed at performing fast real-time processing of collected data, automatically launching follow-up searches when external alerts are received, and identifying interesting neutrino candidates. The KM3NeT online analysis system is able to reconstruct and classify ARCA28 (ORCA24) events in a median time of ~6.8 s (~12.3 s), and to search for MeV CCSN neutrinos, allowing KM3NeT to send alerts to SNEWS with a latency below 20 s and a false alarm rate of less than one per week. Once processed, events are used for follow-up analyses and to identify interesting neutrino candidates, whose public distribution is expected to start soon [3]. The system currently searches for KM3NeT events in coincidence with GWs, GRBs, IceCube neutrinos, FRBs, microquasars, general transients and CCSNe, with more than 1500 alerts analysed since the online follow-up module became fully operational [2]. It is worth mentioning that at the time when automatic follow-ups were still in a preliminary state, KM3NeT data from online processing were used to perform a quick follow-up search of GRB221009A [14], the brightest GRB ever recorded, whose position was above the KM3NeT horizon at the time of the alert. No significant excess was found [15], as also confirmed later by a refined analysis [16]. These results show that KM3NeT has started to play a relevant role in real-time multi-messenger astronomy, thanks to its online analysis system. As the detector grows and its discovery potential increases, the contribution of KM3NeT to this field will become even more significant, especially with the start of its alert sending program.

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