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Online Event Reconstruction and Classification in KM3NET

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Abstract

KM3NeT is the next generation deep-sea neutrino telescopes currently under construction in the Mediterranean Sea. It is composed of two water-Cherenkov neutrino detectors: ARCA and ORCA, located at two sites, southeast of Portopalo di Capo Passero (Italy) and close to Toulon (France), respectively. One of the main scientific goals of KM3NeT is to observe cosmic neutrinos and investigate their sources following a multi-messenger approach, i.e. by combining coincident detection from different telescopes. The combi- nation of an extended field of view and a high duty cycle is crucial for detecting and informing other telescopes about interesting neutrino candidates in a very short time. For this purpose, an efficient online framework can provide, in real time and for each event, reconstructed physical variables, like visible energy and arrival direction. Furthermore, in order to search for neutrino signal, a high background rejection power is needed and deep learning techniques provide promising results. The flexibility and the low amount of information required as input make Graph Neural Networks (GNNs) the perfect candidate to perform real-time event selection in parallel with the event reconstruction processes. In the following, the status of the KM3NeT online framework and the event reconstruction and classification algorithms is presented.

Keywords: Neutrino, Multi-Messenger, Astrophysics, Real Time

1. Introduction

Multi-messenger astronomy is an exciting, rapidly advancing field that involves the coordinated study of cosmic phenomena using different types of ”messengers”—particles or waves that carry information about astrophysical events. These messengers include electromagnetic radiation (e.g., visible light, radio waves, X- rays), gravitational waves, cosmic rays, and neutrinos. Each provides a distinct perspective on the universe, offering complementary information that helps scientists probe the most energetic and mysterious processes in the Universe. Neutrinos, nearly massless elementary particles, play a crucial role in multimessenger astronomy. These elusive particles interact weakly with matter and travel vast distances through the Universe without being

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absorbed or deflected by gas, dust, or magnetic fields. This makes them ideal cosmic messengers for studying the most extreme environments, such as supernovae, black holes, neutron star mergers, and active galactic nuclei. Their detection provides a direct glimpse into processes hidden to traditional astronomical observatories [1].

The goal of the real-time analysis system is to create an efficient and responsive network of experiments that can quickly alert the other telescopes if something interesting is observed. Thanks to its large detection volume, it's almost continuous duty cycle and its excellent angular resolution, KM3NeT is well suited to trigger observatories with limited solid angle visibility to quickly point their instruments in a well-defined direction of the sky. The rapid response requested to efficiently alert the multi-messenger community, requires a fast online event processing algorithms coupled with automated notification systems. The KM3NeT collaboration has developed a Real-Time Analysis (RTA) platform for each of its two detectors, which is able to reconstruct and classify each event with a median latency below 10 seconds. After a general introduction to KM3NeT in Sec. 1, the status of the RTA framework will be described in Sec. 2 with a focus on the online event processing pipeline in Sec. 3.

2. KM3NeT

KM3NeT is a research infrastructure housing the next generation neutrino telescopes located in the Mediterranean Sea: ARCA (Astroparticle Research with Cosmics in the Abyss) is located off the coast of Sicily, Italy, at depth of 3.5 km and it is designed to detect high-energy (multi-TeV) cosmic neutrinos, and ORCA (Oscillation Research with Cosmics in the Abyss) is situated near the coast of Toulon, France, at depth of 2.5 km, is optimized for studying low-energy (sub-TeV) neutrinos and is dedicated to understanding neutrino oscillations [2]. Once completed, the telescopes will have detector volumes between megaton and several cubic kilometres of clear sea water. The detector is composed of long vertical lines, the so-called Detector Units (DUs), anchored to the seafloor, each carrying 18 spherical Digital Optical Modules (DOMs), housing 31 3" Photo-Multiplier Tubes (PMTs) [3]. This 3D array of PMTs allows to detect the Cherenkov light emitted long the path of secondary charged particles produced by the interaction of a neutrino with the matter around the detector. Moreover, thanks to the multi-PMTs technology designed by KM3NeT, even searches for MeV neutrinos, e.g. those expected in Core Collapse Super Nova (CCSN) explosions, can be performed exploiting signals in individual DOMs, by looking for an increased rate of hit coincidences within each DOM. In this way, KM3NeT can cover a very broad energy range that goes from MeV to multi-PeV. At the time of writing, KM3NeT is currently taking data with a partial configuration, 28 strings for ARCA and 23 strings for ORCA, in the so-called ARCA28 and ORCA23 configurations, respectively. Thanks to the technology employed, KM3NeT is able to maintain a high duty cycle and provide near-complete coverage of the sky, ensuring continuous observation of neutrinos. This capability is crucial for detecting transient and variable emissions from cosmic sources. To fully harness the potential of time-domain neutrino astronomy, the KM3NeT Collaboration has developed a real-time event reconstruction and classification system, enabling rapid selection of a high-purity neutrino sample and efficient follow-up of external triggers.

3. Real Time Analyses Framework

The KM3NeT observatory operates using an ”all data-to-shore” approach, meaning that all data collected by the detectors is transmitted to control stations on the shore. There, the Data Acquisition System (DAQ) automatically filters the data to reduce the volume before storage [4]. Prior to being written to storage, the recorded hits and triggered events are processed through the Real-Time Analysis platform. Here, events are continuously processed by two modules. One takes care of the reconstruction and classification of GeV-PeV neutrinos, while the second one searches for MeV neutrinos from individual DOMs. The whole framework is shown in Fig. 1.

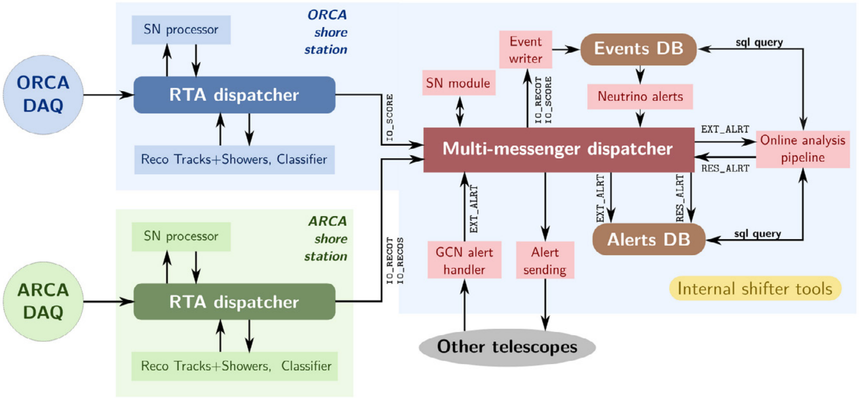

Figure 1: A Simplified Scheme of the Real Time Analysis Framework of Km3net

4. Event Reconstruction and Classification

Depending on flavour and on type of interaction, neutrinos in the GeV-PeV energy range can trigger multiple DOMs within the detector, producing two distinct topological patterns: track-like and shower-like events. Track-like events are associated to muons, which are produced in charge current interaction of muonic neutrinos, crossing the detector volume (a 100 TeV muon can travel for several kilometers) and leaving a narrow and straight signature inside the detector.

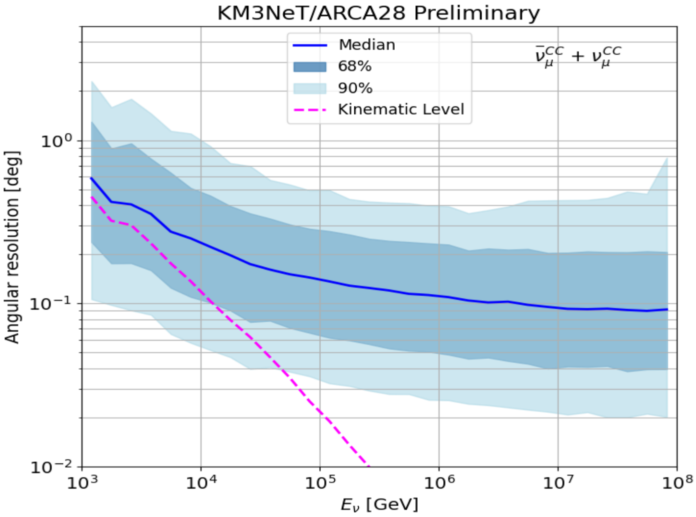

Figure 2: The Angular Resolution of Track Like Events in ARCA28

Thus, these topologies can be used for retrieving the muon arrival direction and pointing to the source sky localization with a very good angular resolution. On the other hand, shower-like events are associated to the production of multiple short-lived particles and can be produced in neutral current interaction of every neutrino flavour or charge current interaction of electronic neutrinos. Be- cause of the limited size of the resulting particle cascade, these events can be fully contained inside the detector volume, allowing for an unbiased computation of the primary particle energy. Furthermore, charge current interactions of tau neutrinos can produce a very peculiar pattern: the secondary tau lepton, whose production is accompanied by a particle cascade, decays into a muon (track-like event) or another shower, giving raise to a very peculiar signature, the so-called ”double bang”.

Because of that event topology classification, KM3NeT has implemented two different algorithms that take care of the reconstruction of a given event as track or as a shower [5]. The same algorithms are used both in the offline and online event processing with two main differences: 1) because the online processing requires to be performed as fast as possible, some steps from the offline reconstruction pipeline are skipped 2) the dynamic calibration are not yet implemented leaving us with a preliminary, and non-refined, knowledge on the detector positioning and timing at the data acquisition time.

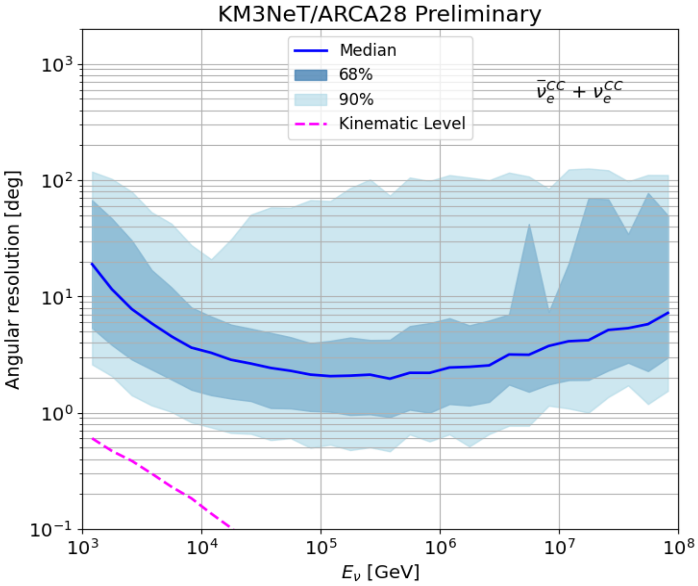

Figure 3: The Angular Resolution of Shower Like Events in ARCA28

In Fig. 2 and Fig. 3 the angular resolution achieved in the case of track-like and shower-like events with ARCA28 detector are shown. Track-like events can achieve a better angular resolution, a median below 0.1° above 1 PeV, then the shower-like events, which instead reach an angular resolution of 2° around 100 TeV. Together with the reconstruction pipelines, machine learning technique to distinguish between noise (atmospheric muons) and signal (neutrinos) events are implemented in the processing chain. Looking deeply at the software infrastructure, some differences arise between the RTA framework of ARCA and ORCA. The main difference concerns the event pro- cessing workflow: while in ORCA each event passes through the two reconstruction and classification steps sequentially, in ARCA the three processes are performed in parallel, which means that the same event is reconstructed as track and shower and classified at the same time, leading to a shorter total processing time. Because of that, two different machine learning approaches have been implemented in the two shore-station. The ORCA RTA framework adopt a Boost Decision Tree, which takes as input the reconstruction outputs, while ARCA relies on Graph Neural Networks (GNN), which does not rely on any processed infos, allowing to perform the classification task in parallel to the reconstruction. The way GNNs work is by converting the raw event structure into a graph in which the hits on the PMTs are the nodes and the connection between them are based on spatial and temporal correlation [6]. In the current detector configuration, the time required to per- form the whole processing of a single event has a median below 7 and 10 seconds for ARCA28 and ORCA23, respectively, and after that, every event is sent to the common Multi-messenger dispatcher in which they are collected and currently used to perform follow-up analyses once an interesting alert is received from other observatories [7].

5. Conclusions

Multi-messenger astronomy has changed our understanding of the Universe by integrating signals from various cosmic messengers, such as light, gravitational waves, neutrinos, and cosmic rays. This has raised the importance of having a well-connected and efficient network of different telescopes able to communicate each other quickly enough to detect transient source and unveil their origin. KM3NeT is a network of neutrino telescopes, currently under construction on the seafloor of the Mediterranean Sea. Together with the neutrino physics studies, the main aim of KM3NeT is the search of cosmic neutrino sources in the Universe. For this reason, a Real-Time Analysis platform has been developed in the recent years, able to perform data processing, which means reconstructing physical properties of an event such as energy and arrival direction, in less than 10 seconds per event. This fast data processing makes KM3NeT a valuable player in the context of multi-messenger astronomy, allowing us to perform follow-up analyses, that are automatically launched once an interesting alert from another experiment has been received and, by the end of the year, to send internal alerts to a network of observatories if something noteworthy has been detected.

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