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Real-time Multi-Messenger Analysis Framework of KM3NeT

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KM3NeT is a multi-purpose cubic-kilometer neutrino observatory in construction in the Mediterranean Sea. It consists of ORCA and ARCA (for Oscillation and Astroparticle Research with Cosmics in the Abyss, respectively); currently both have a few detection lines in operation. Although having different primary goals, both detectors can be used to do neutrino astronomy over a wide energy range, from a few GeV to a few tens of PeV. In view of the growing field of time-domain astronomy, it is increasingly crucial to be able to identify neutrinos in real-time. This online neutrino sample will serve to trigger neutrino alerts that will be sent to the astronomy community and to look for time/space coincidence around external electromagnetic and multi-messenger triggers. These real-time searches can significantly increase the discovery potential of transient cosmic accelerators and refine the pointing directions in the case of poorly localized triggers, such as gravitational waves. In the field of core-collapse supernovae (CCSN), the detection of the MeV-scale CCSN neutrinos is crucial as an early warning. KM3NeT's digital optical modules act as good detectors for these neutrinos. This proceeding presents the status of KM3NeT's real-time multi-messenger activities, including supernova monitoring, online event reconstruction, event classification and selection, alert distribution, and the first test of the selection on data.

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1. Introduction

Multi-messenger neutrino astronomy is a growing field, it benefits from the properties of neutrinos being neutral, almost massless, and only weakly interacting. Neutrinos do not get deflected by magnetic fields during their intergalactic travel thus always point back to their origin. It can provide complementary information when combined with other cosmic messengers, like the traditional photons and the more recent gravitational waves. Neutrinos can be identified in real-time and refine the pointing direction for optical observatories to do quick follow-up studies of transient sources. In the field of core-collapse supernova neutrinos (CCSNs), neutrinos can act as an early warning as neutrinos arrive Earth hours before the photons.

KM3NeT [1], the cubic-kilometer neutrino observatory under construction in the Mediterranean Sea, will be able to detect neutrinos in a large energy range from MeV-scale CCSNs to astrophysical neutrinos up to a few PeV. This proceeding describes the status of KM3NeT's real-time multi-messenger analysis framework.

The proceeding starts with an introduction to KM3NeT and its main science goals in Section 1. Section 2 describes the data flow and the main structure of the real-time framework. Section 3 presents the frameworks' first pipeline of CCSN neutrino burst monitoring. Section 4 and 5 describe the second pipeline, focusing on the online reconstruction, the online neutrino classification and a preliminary event selection. Section 6 gives the first data-MC comparison based on the neutrino selection. Finally, Section 7 summarizes the work and gives the future outlook.

1.1 The KM3NeT Detector

Neutrinos can only be detected indirectly. When neutrinos interact in water, the secondary particles emit Cherenkov light. Detection and analysis of this Cherenkov light are used for the reconstruction of the primary neutrinos.

The KM3NeT infrastructure consists of building blocks, each building block is a 3D array of digital optical modules (DOMs) for recording the Cherenkov light. Each block has 115 vertical detection units (DUs), each DU with 18 DOMs. Each DOM has 31 3-inch PMTs. All the PMT analog signals passing a preset threshold are digitized and sent to shore via optical fibers. At the shore station, online data filtering is performed and the physics events are filtered from background. The arrival time and pulse amplitude observed by the PMTs are used to reconstruct the incoming neutrino's direction and energy.

The DU and DOM spacing are optimized for mainly two scientific goals, making up the two detectors of KM3NeT: ORCA (Oscillation Research with Cosmics in the Abyss) for the oscillation studies with atmospheric neutrinos in GeV scale, and ARCA (Astroparticle Research with Cosmics in the Abyss) for neutrino astronomy studies with astrophysical neutrinos up to a few PeV. ORCA will have one building block, with a vertical 9 m DOM spacing and a horizontal 20 m DU spacing, and ARCA two building blocks with a vertical 36 m DOM spacing and 90m DU spacing. The current KM3NeT detectors have six DUs of ARCA and finished Phase-1 of ORCA (six DUs since January 2020, referred to as ORCA6 from now on).

2. Real-time Alert Analysis Framework

The KM3NeT real-time alert analysis framework has two pipelines: 1) the MeV CCSN monitoring pipeline, 2) the GeV-PeV neutrino alert pipeline.

The MeV CCSN pipeline takes raw PMT data as input, using the coincidences of PMT hits inside each DOM. Each DOM acts as a standalone detector. The main goal of this pipeline is to provide early warning for optical telescopes for the observation of the next Galactic CCSN, as supernova neutrinos will arrive hours before the electromagnetic signals.

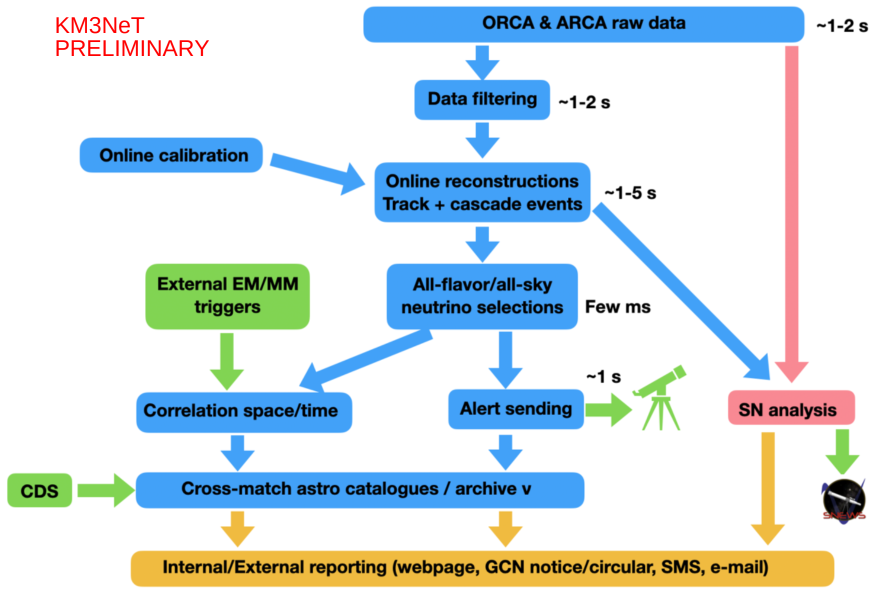

Figure 1: Data flow and the main structures of the KM3NeT real-time analysis framework. The blue boxes and arrows are for the GeV-PeV pipeline, the red box and arrow are for the CCSN pipeline. The green boxes show the alert receiver and the catalogues of the astronomical objects outside the solar system from CDS (Astronomical Data Center). The yellow box shows the internal or external reporting tools if there is a match after the correlation search.

The GeV-PeV pipeline uses the regular triggered events based on the coincidences of multiple DOMs. The goals of the real-time (GeV-PeV) neutrino alert pipeline are: 1) conduct online neutrino point source searches; 2) receive external electromagnetic, gravitational wave, or neutrino alerts and perform online neutrino correlation search based on these external alerts, 3) send all-flavor, all-sky neutrino real-time alerts to external observatories for follow-up. This entails a fast online reconstruction and a fast selection of a high-purity neutrino sample.

Fig.1 shows the data flow and the main structures of the framework. The CCSN pipeline performs searches directly on the raw PMT data, the alerts are sent to SNEWS (SuperNova Early Warning System) [2, 3]. The main processing steps of the GeV-PeV pipeline are represented by the blue boxes, where the raw PMT data are first filtered by the online data filtering [1] tool, then the physics events filtered out of the background undergo event processing which mainly include online event reconstruction and event classification. Based on the classification results, a high-purity event sample is selected for analysis. The analysis of the event sample will produce either interesting KM3NeT neutrino events (e.g., high energy or multiplets) suitable for issuing alerts (via the alert sender) or events correlated with external alerts that will be reported through multiple channels, mainly through GCN (The Gamma-ray Coordinates Network). The processing time is estimated for the main processing steps. In total, the framework's response time is on the order of 10 seconds. Currently, the combined elapsed time for online data filtering, track reconstruction, and classification is 4 s on average for ORCA6.

The event processing is conducted separately at the ORCA and ARCA shore station, but after the event classification, ORCA and ARCA data streams will be combined for analysis and any subsequent alerts.

3. MeV Core-Collapse Supernova Neutrino Pipeline

With the typical MeV-scale energy, one single supernova neutrino can't generate coincident light in multiple DOMs, but the large number of them (up to thousands) during a CCSN burst will result in higher counting rates of individual PMTs and an increase of the number of coincident hit PMTs within a DOM (termed multiplicity). Multiplicity is the main parameter that gives the signal/background separation.

Fig.2 (taken from [4]) shows the expected event rates from simulated CCSN bursts and the background rates as a function of multiplicity. The KM3NeT CCSN pipeline evaluates the multiplicity every 0.1 s in a 0.5 s sliding window. It is operational, sending alerts with false alarm rate less than 1/week, to SNEWS [2, 3]. Alert generation latency is less than 20 s.

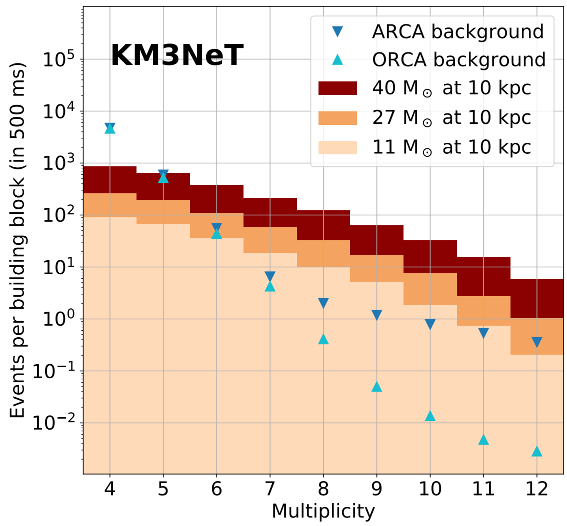

Figure 2: Supernova events expected from 3 simulated progenitors at ORCA and ARCA as a function of different multiplicity values compared with background rates (mainly from ^{40}K decays and bioluminescence) [4].

4. Online Reconstruction of the GeV-PeV Neutrino Pipeline

Neutrinos in the GeV-PeV range can trigger multiple DOMs in the detector, they leave two main types of signatures: 1) track-like events with a visible track, mainly from the charged-current

(CC) interactions of muon neutrinos and partially from the CC interactions of tau neutrinos; 2) shower-like events that have no visible muon track, these events come from the electron neutrino CC interactions, the neutral-current (NC) interactions of all neutrino flavors and the majority of tau neutrino CC interactions.

Based on the two event signatures, KM3NeT event reconstruction can be divided into two types: track reconstruction [5] and shower reconstruction [6]. Online reconstruction uses the same algorithms as in offline, although it does not run the complete reconstruction chain for every event. Optimizations are under way, for example the shower reconstruction may be skipped for events that are clearly down-going atmospheric muons for efficiency reasons.

The muon track of the track-like events gives good directional resolution. Fig.3 shows the angular resolutions of ORCA6 ν_μ CC events, comparing the reconstruction level and a preliminary selection level (see next section). The selection gives a resolution close to the kinematic limit, at 9° around 10 GeV and up to 1° at TeV scale. The angular resolution is limited by the size of the detector and should improve as more DUs get implemented.

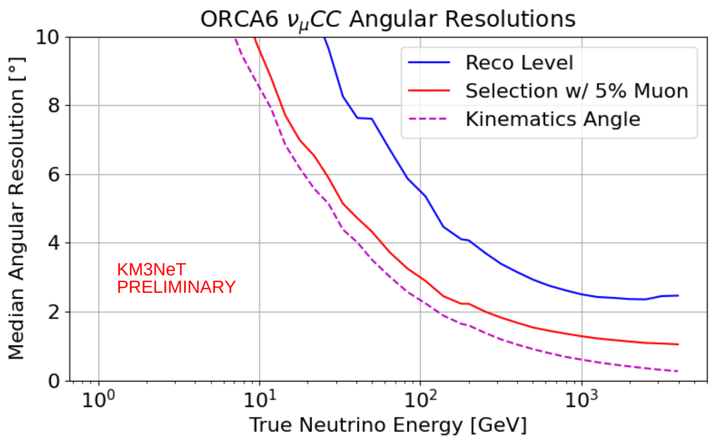

Figure 3: Angular resolution comparisons for preliminary selection and at the reconstruction level with ORCA6, the dashed line is the kinematic angle between the true neutrino and true muon. With the selection, the angular resolution can reach the order of 1° at TeV range.

The online reconstruction is fast: the track direction reconstruction for ORCA6 takes 0.3 s per event on average, the shower reconstruction 1 s. Events with more hits take a longer time, also events with more DUs will take longer, but overall the reconstruction time will stay on the order of 10 s.

5. Online Event Classification

After events are reconstructed, they will undergo classification that selects neutrinos out of the enormous background of atmospheric muons. Each event is evaluated with a classification score indicating the probability of it being a neutrino. The processing of each event takes 0.01s.

The online classification is based on a classifier trained with a gradient boosting decision tree algorithm [7] with simulated ν_μ CC events as signals and atmospheric muons as backgrounds. The training features are physics parameters that provide good separation of neutrinos and atmospheric muons, for example the direction of the reconstructed muon track, the ratio of the track reconstruction's likelihood and number of degrees of freedom, the reconstructed neutrino interaction vertex position, the sum of ToT (Time Over Threshold, proxy for the charge observed by the triggered DOMs), and other geometry, charge and time-based parameters.

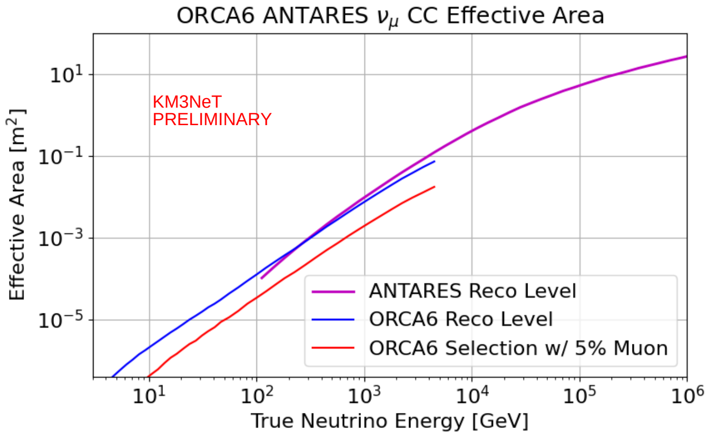

Figure 4: Effective area comparison for ANTARES, ORCA6 at reconstruction level, and the ORCA6 preliminary selection, which selects events uniformly across the energy range.

After the classification, a neutrino sample can be selected - the selection is about choosing the appropriate cut on the classification scores, and the cut can be different depending on different analyses. Fig.3 and Fig.4 show the resolution and effective area with a preliminary selection that gives 5% muon contamination rate. The selection includes a sanity cut (on the triggered hits charge to remove events with sparking DOMs), a cut on the triggered number of hits (>=20) and triggered number of lines (>=2) to remove noise, a cut on the classification score (>=0.9996), and finally a cut to select up-going events (reconstructed cos(zenith) < 0.1). The noise cut is not optimized and thus may be too strict. A full noise simulation is also planned to be added in the classifier training. With this selection, the background muon rate is reduced by 10^6 times while keeping 19% of all-sky signal atmospheric muon neutrinos (38% of the up-going neutrinos), giving roughly 10 atmospheric neutrinos (among them 8.4 ν_μ neutrinos) and 0.5 background atmospheric muons per day in ORCA6. The training of shower classifiers and optimizations for transient source searches are underway.

6. Event Selection Applied on Data

This selection has been applied to the first year of ORCA6 dataset (341 days of livetime). This muon neutrino selection has been optimized to reduce the atmospheric muon contamination to <5%. Neutrino events are weighted with atmospheric fluxes [8] and oscillation parameters with NuFIT5.0 [9]; normal hierarchy is used. No systematics are considered here. On the first year of ORCA6 data, this selects 2879 up-going muon neutrino events. Fig.5 shows the distributions of six parameters: the classification score, the ratio of the track reconstruction likelihood and number of degrees of freedom (the most important training feature for the classifier), reconstructed cos(zenith), reconstructed energy, reconstructed zenith, and the sum of ToT. This first test on data gives a decent

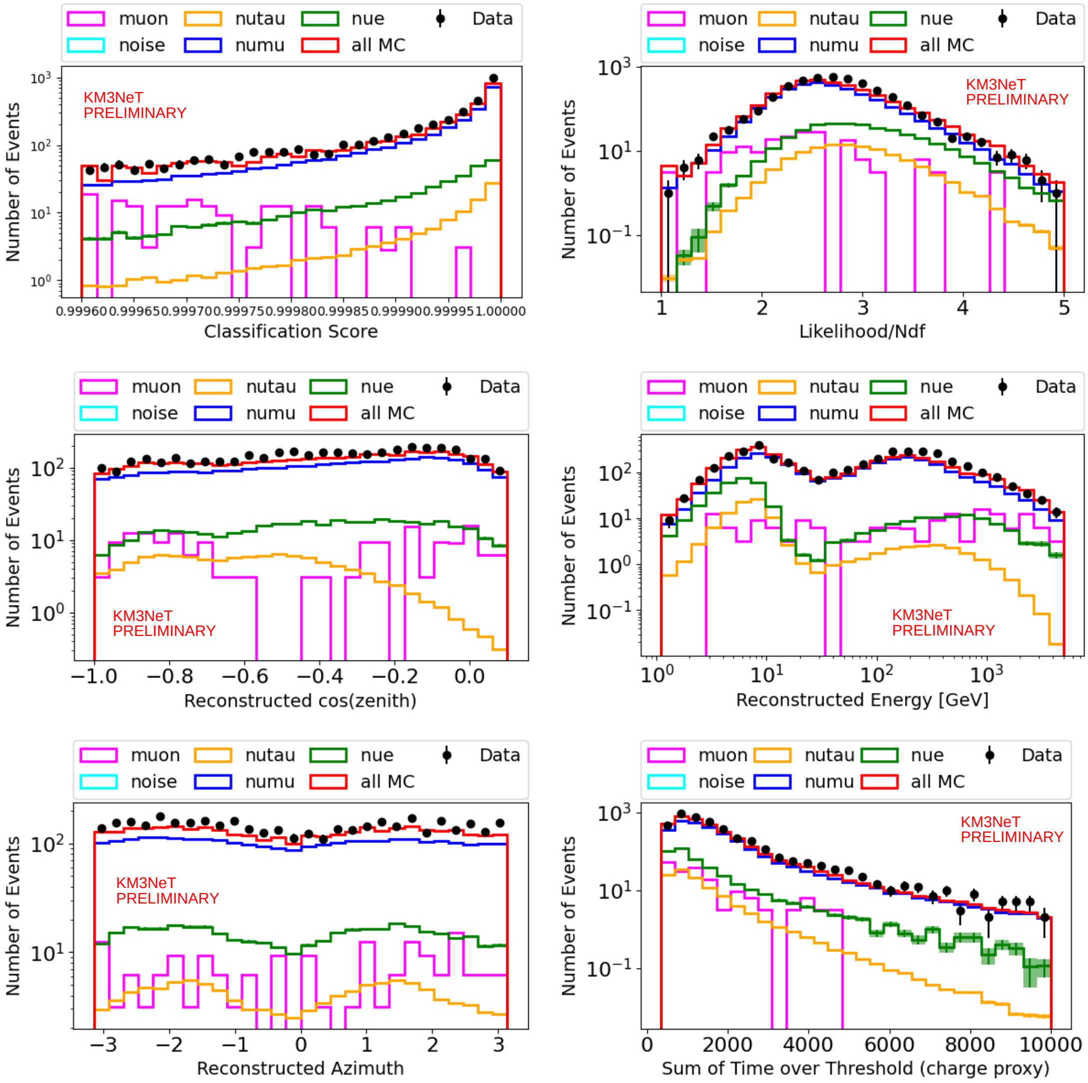

Figure 5: Data/MC comparison of the selected events. Upper left: classification score distribution. Upper right: ratio of track reconstruction likelihood and number of degrees of freedom. Middle left: reconstructed cosine(zenith). Middle right: reconstructed energy. Lower left: reconstructed azimuth. Lower right: sum of ToT of triggered hits. Data is shown in black dots. The blue histogram is for the muon MC (CC and NC combined), green for electron CC neutrinos, yellow for tau neutrino CC, magenta for atmospheric muons, cyan for noise (note all noise are cleaned after the selection, so no cyan lines are actually present), and red histogram is the sum of all the MC events above.

data/MC agreement with the preliminary neutrino selection. In the future, more refinement can be considered taking into account each transient/variable analyses.

7. Summary and Outlook

The excellent angular resolution and large sky coverage of KM3NeT means KM3NeT will become a key contributor to the neutrino multi-messenger community. The current operational six lines of ORCA can already achieve a similar effective area to ANTARES. Our real-time multi-messenger framework is under active development, and we expect to send out KM3NeT multi-messenger alerts beginning in 2022. The alerts will be sent privately during the commissioning phase. After the full validation of the alert system, the main KM3NeT alerts will be distributed publicly.

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