EPJ Web of Conferences **207**, 02006 (2019) https://doi.org/10.1051/epjconf/201920702006
VLVnT-2018

Analysis of High Energy Starting Events with the KM3NeT/ARCA detector

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on behalf of the KM3NeT Collaboration

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Abstract. KM3NeT is a research infrastructure housing the next generation neutrino detectors in the depths of the Mediterranean Sea. The ARCA detector, which is currently under construction, is optimized for neutrino searches from astrophysical sources as well as measurements of the diffuse high energy astrophysical flux. The unambiguous detection of neutrinos of extraterrestrial origin by IceCube has led to the first measurement of a high energy astrophysical neutrino flux. The cutting-edge technology used for the design and construction of KM3NeT Digital Optical Modules along with the properties of sea water allow for a measurement of the neutrino direction with an unpresidented resolution for both track and cascade events. Taking advantage of this angular resolution a method to differentiate track and shower events and a method to reject the atmospheric muon background from track-like events were developed and combined to select a sample of high energy starting events. An analysis for the discovery potential of KM3NeT/ARCA for a diffuse astrophysical neutrino flux using these events is presented.

1 Introduction

KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) is currently under construction at a depth of 3500m, $\sim$ 80 km off-shore Portopalo di Capo Passero in Sicily [1]. When completed, it will consist of two building blocks, each block having 115 vertical Detection Units, instrumenting a volume of approximately 1 km^3. The unambiguous detection of neutrinos of extraterrestrial origin by IceCube and the first measurement of a high energy astrophysical neutrino flux [2] marked the start of high energy neutrino astronomy. Here, an analysis to maximise the discovery potential of KM3NeT/ARCA for a diffuse astrophysical neutrino flux is presented [3], for which a tool to differentiate shower-like from track-like events and a tool to reject incoming events to the detector, were developed. Events were selected by combining these tools to obtain a High Energy Starting Events (HESE) sample.

2 High Energy Starting Tracks (HEST) Analysis

In order to obtain a high purity sample of muons from high energy neutrino events interacting inside the volume of the KM3NeT/ARCA detector, events satisfying the imposed require-

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ments on the track reconstruction quality parameters were selected. To reject events with the incoming track created outside the detector, the reconstructed vertex was required to be located inside a volume slightly smaller than the instrumented one. This requirement alone provides a powerful reduction of the atmospheric muon events, while the efficiency on truly contained HEST neutrino events, with respect to the events fulfilling the quality requirements, is more than 80%, as shown in Fig. 1. To perform the final selection of HEST events, a BDT classifier was trained using as signal truly contained starting track events with $E_\nu > 30$ TeV and as background through-going tracks (ν_μ and $\overline{\nu_\mu}$ CC interacting outside the instrumented volume and atmospheric muon events).

Selecting only HEST events, the discovery potential of KM3NeT/ARCA for an astrophysical power law flux (per neutrino flavor) as described in Eq. 1 was calculated with the Model Discovery Potential (MDP) minimisation method [4] using a cut-and count-approach. The atmospheric muon background was simulated with MUPAGE [5]. The atmospheric neutrino fluxes from Honda [6] and Enberg [7] were used for the conventional and prompt component respectively. MDP was used to find the optimal cuts on the BDT output and the reconstructed muon energy. After imposing these cuts, the contribution of starting track events to the signal (astrophysical neutrino) and background (atmospheric neutrino and muon) samples was 94% and 97%, respectively. KM3NeT/ARCA is expected to make a 3σ (5σ) discovery with 50% probability in ~ 3 (8) years using only HEST, as illustrated in Fig. 2.

$$\Phi_{astro} = \Phi_0 \cdot (E/100\text{TeV})^{-\gamma}, \quad \Phi_0 = 2.3 \cdot 10^{-18}\,\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, \quad \gamma = 2.5 \qquad (1)$$

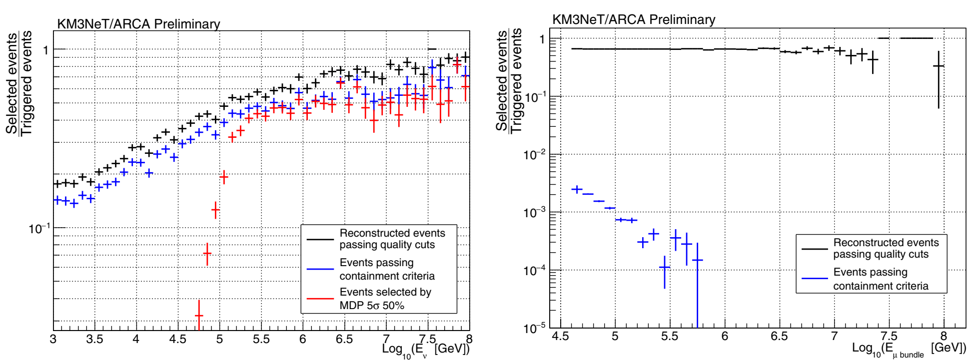

Figure 1. Ratio of the number of events surviving each of the selection requirements over the number of triggered events. Left: Truly contained CC ν_μ and $\overline{\nu_\mu}$ (signal) events with respect to the true E_ν. Right: A sample of atmospheric muon events with respect to E_{bundle}.

The HEST event sample was used to explore the self-veto potential, rejecting atmospheric neutrinos by identifying accompanying muons created at the same atmospheric shower. For this study, two different atmospheric neutrino samples were used: a sample of atmospheric showers simulated with CORSIKA [8] for down-going neutrino events and the standard atmospheric neutrino sample for up-going events. Contrary to using two unrelated samples of muons and neutrinos for the atmospheric background, this more realistic approach allows for the association of muons and neutrinos which come from the same atmospheric shower. The optimal cuts on the BDT output and the reconstructed muon energy were found by the MDP technique. In the final background sample practically all atmospheric neutrinos accompanied by muons were rejected, leading to a 32% reduction of the total atmospheric neutrino background. This resulted in an expected 3σ and 5σ discovery of the astrophysical neutrino flux with 50% probability in ~ 2.25 and 6 years respectively, as illustrated in Fig. 2.

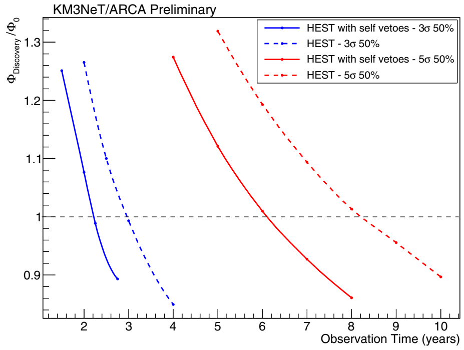

Figure 2. Ratio between the 3σ (blue) and 5σ (red) discovery potential flux normalization factor to the expected neutrino flux normalization Φ_0, as a function of the observation time in years. Solid lines: To explore the self-veto effect samples of both atmospheric neutrino and atmospheric showers simulated with CORSIKA were used. Dashed lines: No self-veto used for atmospheric neutrinos.

3 Contained Shower-like Events Analysis

In order to select a contained shower-like event sample, a tool to differentiate track-like from shower-like events and select the latter was developed. All events reconstructed with the shower reconstruction (defined in [1]) satisfying certain quality criteria and having the reconstructed vertex inside the instrumented volume, were selected. Then, a series of requirements developed to reject track-like events was applied, resulting in a powerful rejection of track-like events as illustrated in Fig. 3 (right plot) with the atmospheric muon sample, while shower-like events are retained with an efficiency $> 95\%$. The efficiency of these requirements is shown for all types of shower-like neutrino events in Fig. 3 (left plot), where a drop of the efficiency for $\overline{\nu_e}$ events at the Glashow resonance energy region is observed. The rejected events had a muon at the final state due to the leptonic decay modes of the W boson, thus the efficiency for real shower-like events remains high. The final step of the classification was performed with a BDT classifier trained using as signal truly contained NC events and as background atmospheric muon events (true tracks).

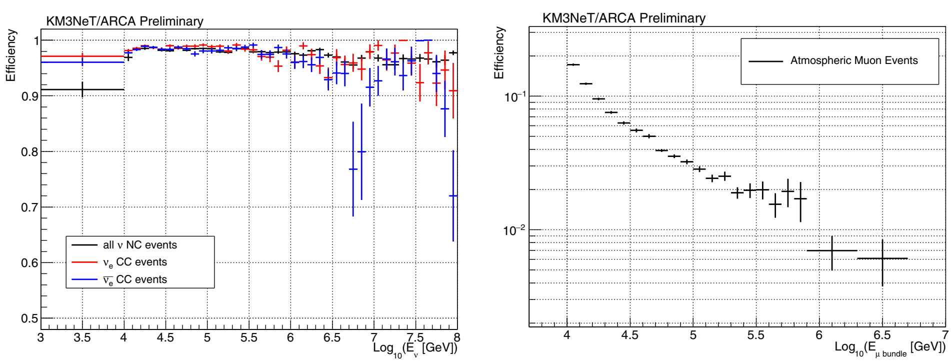

Figure 3. Selection efficiency of the requirements developed to reject track-like events applied to all well-reconstructed events having the reconstructed vertex inside the instrumented volume. Left: For all types of shower-like events with respect to the true E_ν. Right: For atmospheric muon events, used as true track events, with respect to E_{bundle}.

The discovery potential of KM3NeT/ARCA to the astrophysical neutrino flux (Eq. 1) was also calculated with the MDP minimization method using the cut-and-count approach. Again, atmospheric muons and atmospheric neutrinos weighted with Honda and Enberg atmospheric neutrino fluxes, were used for the background. The optimal cuts on the BDT output and the reconstructed shower energy were selected for a 5σ discovery with 50% and

90% probability. After imposing these cuts, the final signal (astrophysical neutrino) and background (atmospheric neutrino and muon) samples comprised 93% and 88% of shower-like events, respectively. KM3NeT/ARCA is expected to make a 5σ discovery with 50% (90%) probability in ~ 0.5 (0.8) years using only shower-like events, as illustrated in Fig. 4.

4 High Energy Starting Events (HESE) Analysis

To perform a HESE analysis the tools described above were combined. All events were processed by the BDT-based tools and a BDT output value was appointed to each event that survived the initial requirements of each tool. Then the MDP minimization method with the cut-and-count approach was employed to find the discovery potential of KM3NeT/ARCA. During this procedure, each event was first categorized either as shower-like or track-like and then, from the track sample, the HEST events were selected. All events labeled as showers or HEST were included in the HESE sample. Finally, the optimal cuts on the BDT output values and the reconstructed track and shower energies were selected. KM3NeT/ARCA is expected to make a 5σ discover with 50% (90)% probability in less than 0.5 (0.8) years, as illustrated in Fig. 4.

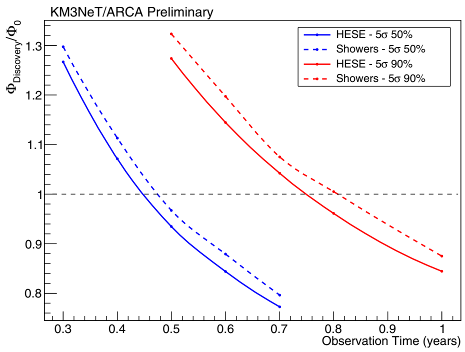

Figure 4. Ratio between the 5σ discovery flux normalization factor and the expected neutrino flux normalization Φ_0 , for 50% (blue) and 90% (red) probability of discovery, as a function of the observation time in years. Solid lines: HESE sample. Dashed lines: Only shower-like events.

5 Conclusion

Two BDT-based tools developed to select high purity samples of HEST and contained shower-like events were combined to perform a HESE analysis for the KM3NeT/ARCA. The self-veto effect was explored using the HEST sample, resulting in a 32% reduction of the total atmospheric neutrino background. Using HESE, without considering the self-veto effect, KM3NeT/ARCA is expected to make a 5σ discovery of the astrophysical neutrino flux, with 50% (90)% probability in less than 0.5 (0.8) years.

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