Reconstruction of neutrino-induced showers with ANTARES
Dorosti Hasankiadeh, Qader

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2013

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Chapter 8

Summary and Outlook

This dissertation reports on measurements and the corresponding data analysis, which was designed to reconstruct and identify neutrino-induced showers in the ANTARES neutrino telescope. The reconstruction of such showers, which are recognised by their local light production, can protrude the sensitivity of a neutrino telescope to all neutrino flavours. Moreover, showers are well-contained events in the detection volume. This characteristic of showers allows for a better energy estimation compared to muon tracks induced by muon neutrinos. In this analysis, we aimed at the reconstruction of a complete set of shower parameters, i.e. the space-time position, energy and direction of neutrino-induced showers. We have exploited and combined two independent event reconstruction algorithms in order to obtain the precise estimation of the shower parameters. A necessary prerequisite for a successful analysis strategy is to efficiently suppress the background of atmospheric muons. We have chosen for defining and combining selection criteria for observables describing the directions and topologies of shower-candidate events. We applied a multivariate data analysis (MVA) in order to efficiently combine the selective cuts and to express them as one discriminating variable. In order to cross-check the final result, we have exploited two independent MVA methods, the K-Nearest Neighbour and the Boosted Decision Tree. The final shower selection strategy is based on stepwise selection criteria expressed by three final cuts, i.e. total deposited charge per event, the MVA score and the energy estimator $\rho$. First we optimise a cut-doublet on total deposited charge per event and a MVA score in order to largely suppress the contamination of atmospheric muons in selected shower samples. The optimal cut-doublet selects neutrino-induced showers from atmospheric muons with a purity better than 99%. Finally, we select cosmic showers among the background of atmospheric neutrinos by optimising a cut on the energy estimator $\rho$. The optimisation procedure relies on the minimization of the value of the average upper limit of the diffuse flux $\Phi_{90\%}$ of cosmic neutrinos, under the assumption of no shower-signal observation. In order to avoid a possible bias in the selection criteria, we have exploited a blind analysis using only 5% of the ANTARES experimental data taken in the period 2008-2010. This blind analysis aimed to verify the consistency of the experimental data and MC simulations, as well as to provide the estimation of the systematic uncertainties. After the selection criteria were finalised, the analysis was unblinded. We have run the analysis on 656 days of the ANTARES experimental data in the period January 2008 to December 2010. The average number of $3.34^{+0.62}_{-0.42}$ and $1.3^{+0.38}_{-0.35}$ signal and background neutrinos, respectively,
are expected after the selection criteria from the diffuse flux of cosmic neutrinos defined in equation 6.4. On the other hand, no experimental event has passed the selection criteria, which is consistent with the background expectation; therefore, we have determined the upper limit on the expected signal of cosmic neutrinos. Assuming a flavour ratio \( (\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1) \) at the detector site and an \( E^{-2} \) spectral shape, our estimation for the upper limit on the diffuse cosmic neutrino \((\nu_\mu + \nu_e + \nu_\tau)\) flux at the 90\% C.L. is:

\[
E[GeV]^2\Phi_{90\%} < 2.53^{+0.42}_{-0.32} \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}
\] (8.1)

This value is equivalent to a limit of \( E[GeV]^2\Phi_{90\%}^{ij} < 0.84^{+0.14}_{-0.11} \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \) on each individual neutrino flavour. 90\% of the expected neutrino signals have energies between 3.1 TeV and 8 PeV. Despite the smaller volume of the ANTARES detector, this result is close to the world’s best upper limit on the diffuse flux of neutrino-induced showers measured by the IceCube detector [col13], i.e. \( E[GeV]^2\Phi_{90\%}^{IC} < 0.23 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \). In addition, our obtained limit on the Southern Sky is complementary to the IceCube limit on the Northern Sky, such that the combination of both results provides a consistent upper limit for the full Sky.

Our limit is only a factor of about 4 above the Waxman and Bahcall upper limit on the cosmic neutrinos [WB98], i.e. \( E[GeV]^2\Phi_{90\%}^{WB} < 2 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \). Running the analysis on a dataset with a total livetime larger than four years may improve the flux upper limit of neutrino-induced showers to a value of \( E[GeV]^2\Phi_{90\%}^{i} < 0.35 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \), which may provide constraints for theoretical models of neutrino production.

**Perspective for the Km3NeT Neutrino Telescope**

The future deep-sea neutrino telescope of multi cubic-km size, KM3NeT [B+11], has been designed for an efficient search for high-energy neutrinos originating from galactic and extragalactic sources. The detection of cosmic neutrinos may provide us with yet concealed information about non-thermal processes in the Universe. Based on the experience of the pilot projects ANTARES, NEMO [C+09] and NESTOR [Rap09], the KM3NeT collaboration plans to equip an active detection volume at the bottom of the Mediterranean Sea with an array of digital optical modules (DOMs), i.e. only digital information will be sent from a DOM to shore for further analysis (see figure 8.1). The direction and energy of neutrinos can be inferred from a precise determination of DOM position, arrival time and total detected charge. For the identification of point-like neutrino sources an angular resolution better than 0.3° can be provided for neutrino energies above 10 TeV.

In addition to Cherenkov photons originating from charged tracks or hadronic showers caused by neutrinos, a DOM is exposed to a random optical background which is due to the decay of radioactive isotopes and biological processes in sea water (see section 3.5). In ANTARES, each photo sensor of 10-inch diameter measures typically a pulse rate of 60 - 100 kHz, mostly single photo electrons produced by \(^{40}\text{K}\) decay (\(\approx 40\) kHz) and by the bioluminescence from the deep-sea fauna causing a constant contribution with occasional bursts of much higher
intensity. These uncorrelated signals are suppressed by requiring local coincidences in nearby photon sensors on each floor of the detector array and a certain minimum number of photon hits on several floors \([H^+12]\). In order to improve the local optical-background rejection, a multi-PMT DOM (figure 8.2) housing 31 3-inch PMTs has been developed and proposed in the KM3NeT Technical Design Report \([B^+df]\). The multi-PMT DOM has a number of advantages compared to an optical module (OM) housing a single large PMT, such as a smaller transit time spread, a longer lifetime, and a better two-photon separation \([AM^+13, Arb10]\) in addition to a simplified charge determination by counting the number of fired PMTs. Small PMTs do not require magnetic shielding, since they are much less sensitive to the Earth’s magnetic field. Moreover a multi-PMT DOM has a higher reliability compared to a single-PMT OM, since failure of one small PMT has a limited effect on its total performance.

In addition, a detector equipped with multi-PMT DOMs may provide a better direction estimation for down-going atmospheric muons, since the sensitive area of the multi-PMT DOM is also extended to its upper hemisphere. Misidentified down-going atmospheric muons present the most severe background for the detection of neutrino-induced showers. As proposed in this dissertation, a way to efficiently reject the atmospheric muons is to select up-going events by exploiting cuts on the event direction. Therefore, a multi-PMT DOM detector may measure neutrino-induced showers providing a higher sensitivity.

The other main advantage of KM3NeT compared to ANTARES stems from its larger detection volume, i.e. a 100 times larger size. A larger detection volume increases the effective area (see section 4.1), which may eventually lead to a higher detection rate for signal neutrinos. Assuming the same detection efficiency as ANTARES, one can expect that the sensitivity of the KM3NeT detector for 1 year of data taking may exceed a sensitivity level of \(E[GeV]^2\Phi_{\text{KM3NeT}}^{90\%} < 10^{-8}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}\), where the limit is mainly determined by the background level. Therefore, the potential of the detection of neutrino-induced showers with KM3NeT is very promising. However, sensitivity studies on a certain configu-
ration of KM3NeT resulted in a less accurate space-time position reconstruction for neutrino-induced showers [Zij11] as compared to ANTARES. This effect is due to a larger spacing between the DOMs chosen for the specific KM3NeT configuration, which increases the effect of light scattering in water. Therefore, the final KM3NeT configuration has to result from a carefully chosen compromise between a maximised detection volume and an optimised space-time position reconstruction.

In addition, due to the large detection volume, KM3NeT will have access to higher energies, i.e. above the PeV energy range. As discussed in section 3.6, in such an energy regime, the track component of tau-neutrino interactions can be long enough so that the double-bang event topology may be detected. Detection of tau neutrinos may furnish a measurement of the neutrino flavour ratio. The expected standard neutrino-flavour ratio on Earth is $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, assuming neutrino production through the decay of charged pions caused by interactions of high-energy protons with photons or nucleons [LP95] and taking into account neutrino oscillations. Any observed deviation from the standard neutrino-flavour ratio can either provide constraints on astrophysical models [KW05] or probe for new physics [LP95, AJY00].