PROCEEDINGS OF SCIENCE

All-sky diffuse astrophysical neutrino flux with KM3NeT/ARCA data

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KM3NeT/ARCA is a rapidly evolving neutrino detector in the Mediterranean Sea. The capability of the detector to measure the diffuse astrophysical neutrino flux was recently demonstrated by the observation of an ultra-high-energy neutrino of astrophysical origin. In this contribution, an analysis of KM3NeT/ARCA data, employing machine learning techniques and advanced statistical methods is presented, as well as a fit to the parameters of the diffuse flux. The latest results for the diffuse cosmic neutrino flux with KM3NeT/ARCA will be reported.

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1. Introduction

Cosmic accelerators such as supernova remnants, active galactic nuclei, and gamma-ray bursts are considered to be the sources of high-energy cosmic rays. When these particles interact with surrounding matter or radiation fields through hadronic processes —primarily pp and $p\gamma$ interactions— they produce high-energy neutrinos. Neutrinos, being electrically neutral and weakly interacting particles, can travel cosmological distances without deflection or attenuation, making them unique messengers of the physical conditions at the edges of the Universe. These observations form a central pillar of multi-messenger astrophysics, complementing photon- and gravitational wave-based studies.

Neutrino telescopes are designed to observe these elusive particles by capturing the Cherenkov light emitted by secondary charged particles generated in neutrino interactions with the surrounding medium, typically water or ice. In this analysis, signal includes neutrinos and antineutrinos of all three flavours (ν_e, ν_μ, ν_τ), produced via both charged-current (CC) and neutral-current (NC) interactions. The flux of astrophysical neutrinos is commonly modelled as an unbroken power-law spectrum, and the performance of neutrino telescopes is assessed using detailed Monte Carlo (MC) simulations. At production, the expected flavour composition is approximately $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, a result of pion decay chains. However, due to flavour oscillations during their propagation over cosmic distances, the flavour ratio is expected to evolve to roughly $1 : 1 : 1$ by the time the neutrinos reach Earth.

2. Analysed data

Two deep-sea Cherenkov neutrino detectors are currently being deployed in the Mediterranean Sea as part of the KM3NeT research infrastructure [1]. The first, known as KM3NeT/ARCA, is situated near Capo Passero, Italy at a depth of 3500 m and is optimised for the detection of high-energy astrophysical neutrinos in the TeV–PeV range. The second, KM3NeT/ORCA, lies offshore Toulon, France at 2500 m depth and is designed for studies of atmospheric neutrino oscillations.

Both detectors share the same technology built around the Digital Optical Module (DOM) [2], a pressure-resistant glass sphere housing 31 3"-photomultiplier tubes (PMTs). Eighteen DOMs are vertically arranged along a flexible line to form a Detection Unit (DU), anchored to the seabed and stabilised by a buoy at the top. Upon full deployment, KM3NeT/ARCA will consist of two building blocks, each comprising of 115 DUs with an on average distance of 90 m between them and DOMs vertically spaced by 36 m.

Construction proceeds in phases allowing data acquisition to begin with partially completed configurations. Data-taking periods are named after the number of active DUs at the time. In this contribution, an analysis of the combined ARCA6-8-19-21 periods is presented. After applying quality criteria, the number of analysed days for each configuration is: ARCA6 ran from May 2021 to September 2021 [92 analysed days], ARCA8 from September 2021 to June 2022 [212 analysed days], ARCA19 from June 2022 to September 2022 [48 analysed days] and ARCA21 from September 2022 to September 2023 [287 analysed days].

Currently, 51 DUs have been deployed within the ARCA detector.

3. Event selection

The goal of this contribution is to compute the sensitivity and upper limits for a flux of cosmic neutrinos using the data of ARCA6+8+19+21 detector configurations, as well as to fit the parameters of the diffuse cosmic (anti)neutrino flux. For these measurements to be possible, a high purity cosmic (anti)neutrino sample needs to be achieved by selecting neutrino-like physical events. A physical event is defined as a cluster of photon hits recorded by PMTs within a fixed spatial and temporal coincidence window. Besides genuine Cherenkov photons, the PMTs register uncorrelated noise, chiefly from ^{40}K decays and marine bioluminescence. These random hits are suppressed by applying quality requirements to the reconstruction variables.

The astrophysical signal consists of up-going neutrinos of astrophysical origin, including all three flavours and both CC and NC interaction channels, reconstructed as track-like events. The primary sources of background are atmospheric neutrinos —modelled using the Honda [3] and Enberg [4] fluxes with adjustments accounting for the cosmic ray knee— and atmospheric muons. The unbroken power is law parametrised as:

$$\Phi_{\nu+\bar{\nu}}(E) = \frac{dN}{dE} = \phi_0 \cdot 10^{-18} \cdot \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma} \left[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\right] \tag{1}$$

As a baseline, the IceCube measurement parameters [5], $\phi_0 = 1.44$ and $\gamma = 2.37$, are used. A preselection based on the goodness of the track fit and the track length, retaining only tracks reconstructed as up-going —eliminating the vast majority of downward-going events— is realised after extensive data-MC comparisons. A *blind analysis strategy*, where all selection criteria were optimised using Monte Carlo simulations and only 10% of the recorded data, is followed. Since the up-going cut is at zenith > 90° the recently observed KM3-230213A [6] is not included in the sample.

3.1 Boosted Decision Tree and optimisations

To further enhance signal purity, since atmospheric muons —down-going, inaccurately recostructed as up-going— are still present in the sample, a Boosted Decision Tree (BDT) classifier implemented with ROOT TMVA [7] is employed. The BDT used is the one optimised in previous iterations of the analysis, [8], [9], [10] trained separately for the ARCA6/ARCA8 and ARCA19/ARCA21 detector configurations treating well-reconstructed up-going muon (anti)neutrino CC events as signal and misreconstructed atmospheric muons as background.

Additional cuts are applied after the BDT score cut on the ARCA6 configuration to further suppress the atmospheric muon contamination. To address the limited statistics of the atmospheric muon Monte Carlo simulations for all ARCA configurations at high BDT scores and energies, the atmospheric muon contribution is estimated by fitting the reconstructed energy spectrum. An optimal energy cut threshold is obtained for each configuration based on the Model Rejection Factor technique [11].

4. Statistical analysis

Upon reaching a final selection, data can be statistically analysed in comparison with MC for the extraction of various results. A Bayesian and a frequentist interpretation of probability are considered to assess the extent to which the choice of statistical interpretation influences the sensitivity. The impact of the choice is explored through for both integrated and differential sensitivities. The Bayesian framework is moreover used to provide a fit of the cosmic neutrino diffuse flux parameters.

For both frameworks, the same systematic uncertainties are taken into account.

4.1 Bayesian framework

A binned maximum likelihood method as the one described in [12] is employed. A likelihood function, eq. 2, is constructed as the product over all reconstructed energy bins i, of Poisson probabilities for observing N_i events, given an expected background B_i and a signal contribution $\phi_0 S_i(\gamma)$ calculated for a given spectral index and normalisation:

$$L(N; S(\gamma), B, \phi_0) = \prod_i \text{Poisson}(N_i, B_i + \phi_0 S_i(\gamma)). \tag{2}$$

To incorporate both statistical and systematic uncertainties Gaussian priors are introduced. Thus, the marginalisation of the posterior defined in eq. 3 can provide an estimation of the cosmic parameters:

$$p(\phi_0, \gamma; N) = \int L(N; S(\gamma), B, \phi_0) \cdot \pi(B_i) \cdot \pi(S_i(\gamma)) \cdot \pi(\phi_0, \gamma) \cdot \prod_i dB_i dS_i(\gamma). \tag{3}$$

If instead, the posterior is marginalised over the cosmic parameters, a fit of the atmospheric background normalisation can be extracted. For the small detectors ARCA6/ARCA8 a likelihood function is constructed in which the background fluctuates independently for each energy bin and thus the estimation of the normalisation is not performed. For the extended ARCA19/ARCA21 detectors, the background is assumed to fluctuate in the same manner for all energy bins. The two likelihoods are then multiplied to perform the fit of the cosmic parameters.

4.1.1 Astrophysical parameters fit

The marginalisation of eq. 3 allows for a computation of the cosmic neutrino diffuse flux parameters. The best estimated points for the cosmic parameters are a normalisation of $\boldsymbol{\phi_0} = \mathbf{3.03}$ and a spectral index of $\boldsymbol{\gamma} = \mathbf{3.0}$. Credible regions for the cosmic parameters at 68%, 90% and 99% CL together with the best point estimators are shown in Figure 1 (left). The upper limits for the combined ARCA configurations are shown in Figure 1 (right) in comparison with IceCube and ANTARES [13] 1-flavour best-fit flux.

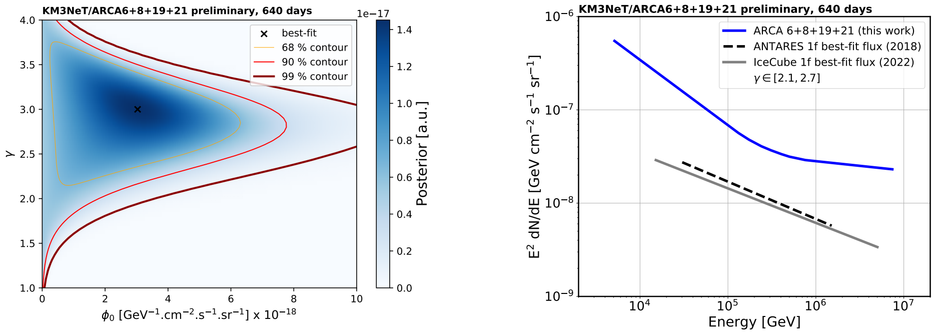

Figure 1: Marginalised posterior distribution at final selection level with unblinded data. The 68%, 90% and 99% credible regions for the cosmic parameters together with the best point estimators **(left)**, and the envelope of upper limits at 90% CL for selected γ in range [2.1, 2.7] for the combined ARCA6+ARCA8+ARCA19+ARCA21 periods, computed for the central 90% energy range of the signal events **(right)**, are shown.

4.1.2 Background normalisation fit

When focusing on ARCA19 & ARCA21 configurations, the best estimation of the background normalisation (atmospheric muons and atmospheric neutrinos) returned a value of $N_{\mathbf{bkg}} = \mathbf{1.53} \pm \mathbf{0.24}$ in good agreement with IceCube reported results [14]. The marginalisation over the cosmic parameters can be seen in Figure 2 (left) along with the recostructed energy distribution of ARCA21, after upscaling the background by the estimated value (right).

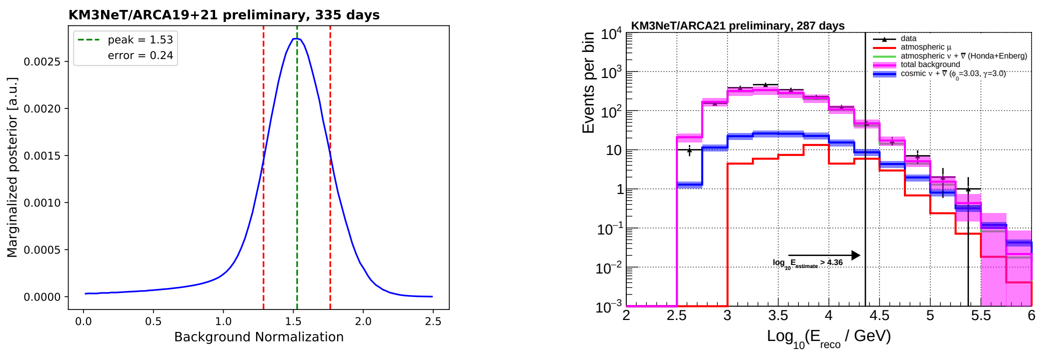

Figure 2: Background normalisation estimation for the combined ARCA19 & ARCA21 configurations **(left)**, and distribution of the reconstructed energy of ARCA21 after using the best estimations for the background normalisation and the cosmic parameters **(right)**. The total background (purple) and the signal (blue) are shown with their total uncertainty bands. The vertical line shows the optimal energy cut threshold mentioned in section 3.1.

4.2 Frequentist framework

The frequentist framework relies also on a Poisson likelihood approach. The event selection and the BDT score cut are exactly the same as in the Bayesian approach, but the reconstructed energy cut threshold mentioned in section 3.1 is not applied.

Systematic uncertainties —of the same order as the Bayesian framework— are added as a combination of nuisance parameters and pull-terms. A bin-by-bin uncertainty in the energy bins is attached to atmospheric muons and atmospheric neutrinos. An uncertainty is also assumed for the total normalisation of cosmic neutrinos.

Assuming that the asymptotic limit is hold, a χ^2 can be derived as follows:

$$\chi^2_\alpha = \sum_i 2\left(P_i - D_i + D_i \ln\frac{D_i}{P_i}\right) + \sum_i \left(\frac{\alpha_{\mathrm{atm},i}}{\sigma_{\mathrm{atm}}}\right)^2 + \left(\frac{\alpha_{\mathrm{muon},i}}{\sigma_{\mathrm{muon}}}\right)^2 + \left(\frac{\alpha_S}{\sigma_S}\right)^2. \quad (4)$$

The first term is the standard Poissonian statistics-only χ^2 [18]. D_i represents the data content in the i-th bin either observed or simulated by MC, where i refers to the E_{reco} bins. $P_i = (1 + \alpha_S)\, S_i + \left(1 + \alpha_{\mathrm{atm},i}\right) B_{\mathrm{atm},i} + \left(1 + \alpha_{\mathrm{muon},i}\right) B_{\mathrm{muon},i}$ represents the prediction in the same bin taking into account signal plus background. The contents of the D_i bins are always generated according to the IceCube values reported in section 3. On the contrary, P_i values are evaluated for diferent values of ϕ_0 and γ. The second and third terms correspond to the pull-terms associated with the systematic uncertainties outlined above. For every test point, (ϕ_0, γ), eq. 4 is minimised leaving the nuisance parameters α free.

To calculate the sensitivity, one has to adhere to the following steps. First, introduce the signal strength μ, a parameter that regulates the amount of signal. This is a simple scaling factor of the signal. Then, pseudo-experiments are generated for specific values of injected μ by a Poisson smearing taking into account statistical and systematics uncertainties. For each pseudo-experiment of a given μ, χ^2_α is minimised with respect to nuisance parameters α to obtain χ^2_{min}. Then, the test statistic λ, defined as the difference between the χ^2 at $\mu = 0$ and χ^2_{min}, is evaluated:

$$\lambda = \chi^2(\mu = 0) - \chi^2_{\mathrm{min}}. \quad (5)$$

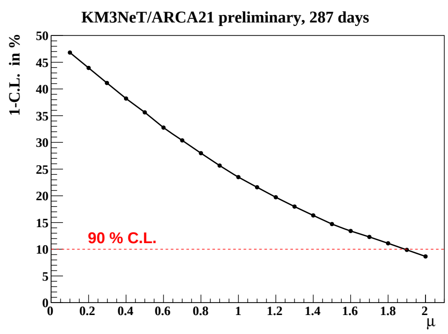

Figure 3: Frequentist sensitivity estimation for ARCA21. The curve shows 1−CL as a function of the signal strength μ. The intersection with the horizontal dashed line at 10 provides the sensitivity of ARCA21 assuming as baseline the IceCube flux [5].

To calculate the sensitivity for a specific μ, one has to integrate the distribution of $\lambda(\mu)$ from the median of the background-only hypothesis distribution, $\lambda(\mu = 0)$ up to infinity. In Figure 3, the complementary of this integral confidence level $(1 - \mathrm{CL})$ is shown as a function of μ. The value of the signal strength μ, for which the test statistic λ is greater than the median of the background only distribution 90% of the cases, is referred to as the sensitivity in the signal strength. One can see from Figure 3 that this value is $\mu = 1.9$, therefore the sensitivity of ARCA21 to the flux normalisation reaches a value of $\phi^{90}_{\mathrm{ARCA21}} = 1.9 \cdot \phi_0$ with $\phi_0 = 1.44$ the baseline from the IceCube measurement [14].

4.3 Differential Sensitivity

When computing differential sensitivity each bin —in terms of true (simulated) neutrino energy— is treated independently (references [15], [16] and [17] are examples of the method applied in a frequentist framework). The computation is performed as described in sections 4.1 and 4.2 but within a specific true neutrino energy range each time. In contrast to the integrated sensitivity, the differential limits are quasi-independent of the flux, so a spectral index $\gamma = 2$ is chosen in the computations.

4.3.1 Bayesian

Firstly, the differential sensitivity is computed using the Bayesian framework. The selection is re-optimised for each true energy bin. The result of the computation can be seen in Figure 4.

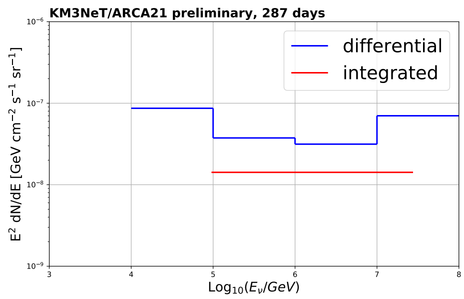

Figure 4: Differential sensitivity of ARCA21 configuration for a cosmic neutrino flux of $\Phi \sim E^{-2}$ assuming a Bayesian framework, compared with the integrated sensitivity for the same flux, both at a 90% CL.

4.3.2 Frequentist

Secondly, the technique is used under the frequentist framework. The same re-optimisations as in the Bayesian case are made. The result of the computation can be seen in Figure 5. It is interesting to note that the sensitivities at $5 - 7$ $\log E_{\text{true}}$ bins do not differ much.

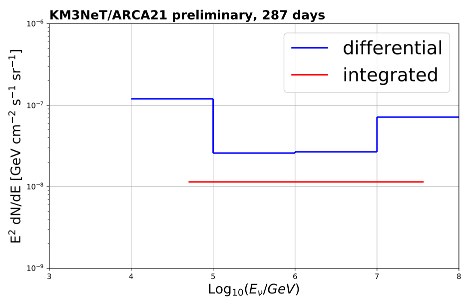

Figure 5: Differential sensitivity for ARCA21 configuration under a frequentist assumption for a cosmic neutrino flux of $\Phi \sim E^{-2}$ compared with the integrated sensitivity for the same flux, both at a 90% CL.

5. Conclusions and outlook

This contribution presents an analysis of the complete dataset acquired with the initial ARCA configurations of significant instrumented volume —specifically ARCA6, ARCA8, ARCA19, and

ARCA21— aimed at probing a three-flavour diffuse astrophysical neutrino flux. Using a Bayesian interpretation of the probability, a fit of the cosmic flux parameters returned a normalisation of $\phi_0 = 3.03$, a spectral index of $\gamma = 3.0$ and an atmospheric background normalisation —extracted from the combined ARCA19 & ARCA21 configurations— of $N_{\mathrm{bkg}} = 1.5 \pm 0.24$.

Consequently, additional statistical methods developed in KM3NeT for extracting the ARCA21 —larger and with longer uptime— detector configuration sensitivity were showcased. Integrated and differential sensitivities have been computed following Bayesian and frequentist approaches. The differential sensitivity was computed for each energy bin and then was compared with the integrated one. A differential sensitivity can be more informative of the expected energy spectrum. The reconstructed direction information (cosine of zenith angle) in the likelihood will be included in future developments of the analysis.

This contribution reports the latest results for the diffuse cosmic neutrino flux search with KM3NeT/ARCA and the alternative tools developed for this endeavor.

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