

Search for a diffuse astrophysical neutrino flux from the Galactic Ridge using KM3NeT/ARCA data

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Several theoretical models predict and describe the properties of part of the diffuse neutrino flux, originating from the interaction of Galactic cosmic rays with the interstellar medium matter located in the centre of our Galaxy. This neutrino flux is expected to be of the same order of magnitude as the diffuse γ -ray flux measured by Fermi-LAT, close to the Galactic plane. Recently hints by the ANTARES Collaboration, at a significance level over 2σ , and the observation by the IceCube Collaboration, at a significance level of 4.5σ , of a high-energy neutrino emission from the Galactic plane have been reported. For these reasons, and considering the privileged position of the KM3NeT/ARCA telescope, being located in the Northern hemisphere, data have been analysed searching for a possible excess of events coming from an extended region, with Galactic coordinates $|l| < 30^\circ$ and $|b| < 2^\circ$, namely the Galactic Ridge. In this contribution, the result of the analysis exploiting data gathered with KM3NeT/ARCA in the period in which comprises 6 or 8 active detection units is presented, showing the capabilities and performance of KM3NeT.

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1. Introduction

1.1 Diffuse neutrino emission from the Galactic Ridge

The Galactic plane is the most evident source in the sky in all the electromagnetic wavelengths. These photons can be produced either in specific point sources, positioned on the Galactic plane, or by the interaction of cosmic rays (CRs) with the interstellar medium matter (ISM), located in the center of our Galaxy. A significant fraction of energy released during these interaction processes is transformed into short living particles, that can decay into γ -rays and neutrinos. While photons can be produced by energy-losses of electrons, interacting with magnetic fields or ISM, neutrinos can be produced only in the decays of particles produced in hadronic interactions, representing therefore a unique probe of acceleration and interaction sites of CRs. Several theoretical models have been developed in the past years, to try to constrain the flux of neutrinos originated inside the Galactic plane [1–3]. The strict relation that link γ -rays and neutrinos, produced via hadronic interactions, allows to constrain the expected neutrino fluxes thanks to measured CRs local properties and to γ -rays measurements themselves, performed both by space-based telescopes and by detectors located on Earth. In the specific, the predicted neutrino flux is expected to be of the same order of the γ -ray one, and in the innermost part of the Galactic plane, defined here $|l| < 30^\circ$ and $|b| < 2^\circ$, namely the Galactic Ridge, the CRs spectrum should be described by a harder spectral index with respect to the one locally measured at Earth. The ANTARES Collaboration reported an excess of events coming from the Galactic Ridge incompatible with the background expectation at $\sim 96\%$ confidence level [4], and at the end of June 2023, IceCube Collaboration has reported the first observation of high-energy neutrinos from the Galactic plane, with a statistical significance of 4.5σ [5].

1.2 KM3NeT neutrino telescope

KM3NeT¹ is the next-generation neutrino telescope project that will instrument, in its final configuration, an overall volume of several cubic kilometres of sea water [6]. KM3NeT comprise two different instrumented regions, placed in separate locations: KM3NeT/ARCA², off-shore the Sicilian coast at a depth of about 3500 m, optimised for searching of neutrinos from astrophysical sources, and KM3NeT/ORCA³, off-shore the French south coast, that will study neutrino properties exploiting atmospheric neutrinos. The two detectors share the same technology and neutrino detection principle: namely a 3D array of photosensors, called digital optical modules (DOM) [7], capable to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. The main difference between the two detectors consists in the density of photosensors, which is optimised for the study of neutrinos in the few-GeV region for ORCA and the TeV-PeV energy range for ARCA. The detectors are built with detection units (DUs), which stand on the sea bottom and comprise 18 DOMs each. In its final configuration the KM3NeT/ARCA telescope will consist of two building blocks of 115 vertical detection units each. Both sites however are in the Northern hemisphere at a latitude between 36° and 43° North, allowing to observe upgoing events coming from most of the sky. In fact, looking at the KM3NeT sky coverage, reported in Figure 1,

¹KM3NeT is an acronym for ‘Cubic Kilometre Neutrino Telescope’

²ARCA stands for Astroparticle Research with Cosmics in the Abyss

³ORCA stands for Oscillation Research with Cosmics in the Abyss

we can see that most of the galactic plane, including the Galactic Ridge, is fully visible through upgoing events.

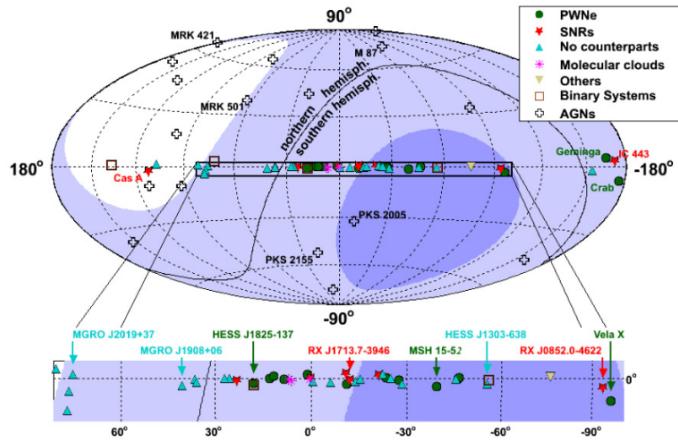


Figure 1: Sky coverage of a neutrino telescope located in the Mediterranean sea, in galactic coordinates. Dark (light) blue shaded areas represent visibility over 75% (25%). Some known astrophysical objects are marked. Figure taken from [6].

2. Analysis

In the following sections, a data analysis to search for a diffuse neutrino flux coming from the Galactic Ridge is reported. In the specific, data gathered with 6 and 8 active DUs of the KM3NeT/ARCA detector have been exploited, for a total lifetime of 102 days and 212 days, respectively.

2.1 Event selection

The events considered in the analysis are track candidate events, generated by ν_μ charged-current interactions, that have passed quality selection criteria. To further reduce the surviving background, represented by atmospheric muons, a Boost Decision Tree (BDT) has been trained in order to classify and reject these events (developed in synergy with [8]). In Figure 2 the BDT score data-Monte Carlo distribution is shown.

An optimal event selection is then derived, through the minimization of the Model Rejection Factor (MRF) [9], specifically for a signal flux with spectral index $\Gamma_\nu = 2.4$. The optimal region, from which to require that reconstructed directions of the track events should come from, has been found to be $|l| < 31^\circ$ and $|b| < 5^\circ$, due to the angular resolution of the detector in the considered configurations. The whole event selection has been carried out following the blinding policies of the KM3NeT Collaboration.

2.2 Method

The methodology adopted for the analysis is an on-off technique, similarly to what has been done in [4] and [10]. The on-region is defined, from the optimization procedure described in section

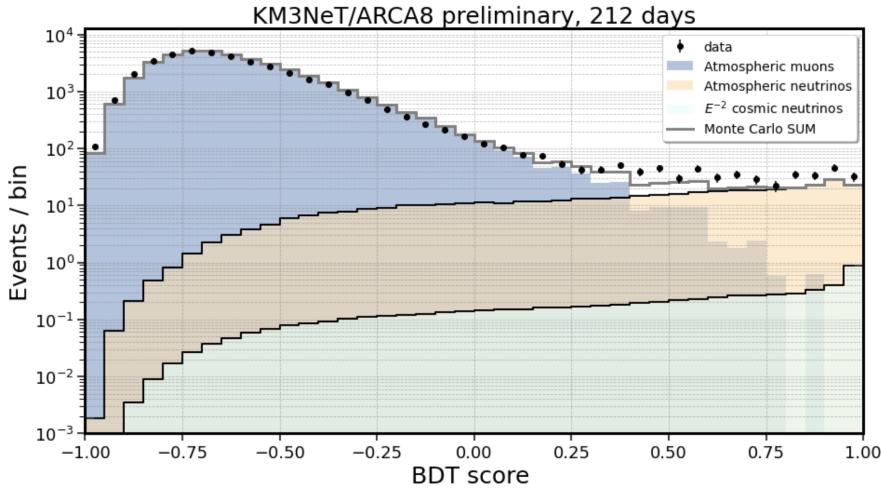


Figure 2: Data-Monte Carlo comparison for Boost Decision Tree output score, evaluated on test sample. Classification among atmospheric muons (blue shaded distribution) and neutrinos (orange and green shaded area).

2.1, to be $|l| < 31^\circ$ and $|b| < 5^\circ$. The background expectation instead is directly estimated from off-regions in the data, which have been selected so as to have the same sky coverage of the on-region and are shifted in right ascension, while avoiding also the region of the Fermi Bubbles. The expected neutrino signal has been simulated following the standard Monte Carlo chain developed within the KM3NeT collaboration [11], assuming the signal to be originated inside the Galactic Ridge. Each simulated event has been then weighted assuming a single power-law spectrum, of the form $\Phi_\nu(E) = \frac{dN_\nu}{dE_\nu} = \Phi_0 \times \left(\frac{E_\nu}{E_0}\right)^{-\Gamma_\nu}$ with a normalization energy E_0 set at 40 TeV, for convenience. The selected events are binned in function of the reconstructed energy, and the statistical analysis, based on the same procedure developed in [4], adopts the following binned likelihood approach:

$$\mathcal{L}(N_i; S_i^{\Gamma_\nu}, B_i, \Phi_0) = \prod_{i=1}^{12} \text{Poisson}(N_i, B_i + S_i^{\Gamma_\nu}) \quad (1)$$

where N_i is the number of events observed in the on-region in each energy bin, B_i the background derived from the off-regions and $S_i^{\Gamma_\nu}$ is the signal expectation, derived from Monte Carlo simulations for a given spectral index Γ_ν and normalization flux Φ_0 . A posterior probability distribution is derived, following a Bayesian approach, in order to include statistical and systematic uncertainties, and assuming a flat prior for the two parameter of interest: the neutrino spectral index Γ_ν and normalization flux Φ_0 . From the profiled posterior probability then upper limits and sensitivities are derived.

2.3 Results

In Figure 3 the unblinded energy distributions are shown for respectively KM3NeT/ARCA6 and KM3NeT/ARCA8. No excess of events has been found with respect to the background expectation. Therefore the 90% C.L. upper limits have been calculated and reported in Table 1.

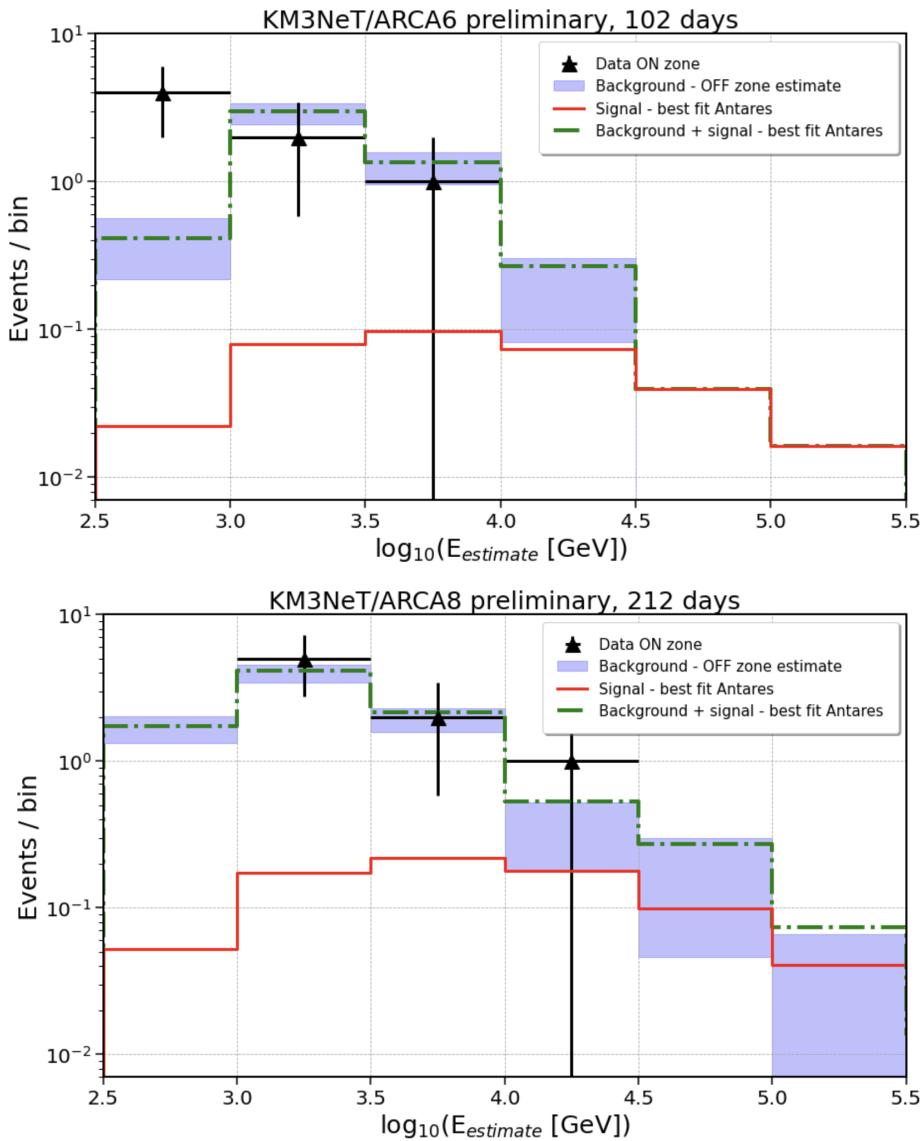


Figure 3: Energy distribution of selected events for KM3NeT/ARCA with 6 (**top**) and 8 (**bottom**) active detection units. The blue bands represent the background estimation derived from the off-regions, with the associated statistical error. The black points represent the data found in the on-region while the red solid lines represent the numbers of events expected in KM3NeT/ARCA6 and ARCA8 data sets respectively, assuming the ANTARES best-fit flux found in [4]. The green dashed lines show the sum of the expected signal and background.

In Figure 4 the best-fitting flux obtained from the IceCube Collaboration [5] for two templates models is reported, together with the ANTARES results [4] and KM3NeT upper limits. Since the analysis methodology adopted by IceCube is based on a full-sky template search, the ANTARES and KM3NeT limits has been integrated over the solid angle extension of the Galactic Ridge.

90% C.L. upper limits			
Γ_ν	ARCA6	ARCA8	ARCA6+8 combined
2.2	8.6×10^{-5}	4.5×10^{-5}	3.4×10^{-5}
2.3	2.7×10^{-4}	1.3×10^{-4}	1.1×10^{-4}
2.4	8.2×10^{-4}	3.9×10^{-4}	3.0×10^{-4}
2.5	2.3×10^{-3}	1.1×10^{-3}	9.0×10^{-4}
2.6	6.5×10^{-3}	2.9×10^{-3}	2.5×10^{-3}
2.7	1.7×10^{-3}	7.4×10^{-3}	6.8×10^{-3}

Table 1: 90% C.L. upper limits under a single power-law assumption, referred to in the text as Φ_ν , for a reference energy $E_0 = 1$ GeV and with spectral indices Γ_ν ranging from 2.2 to 2.7 for KM3NeT/ARCA6, KM3NeT/ARCA8 and the combined data sets. All the results are expressed in units of $\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

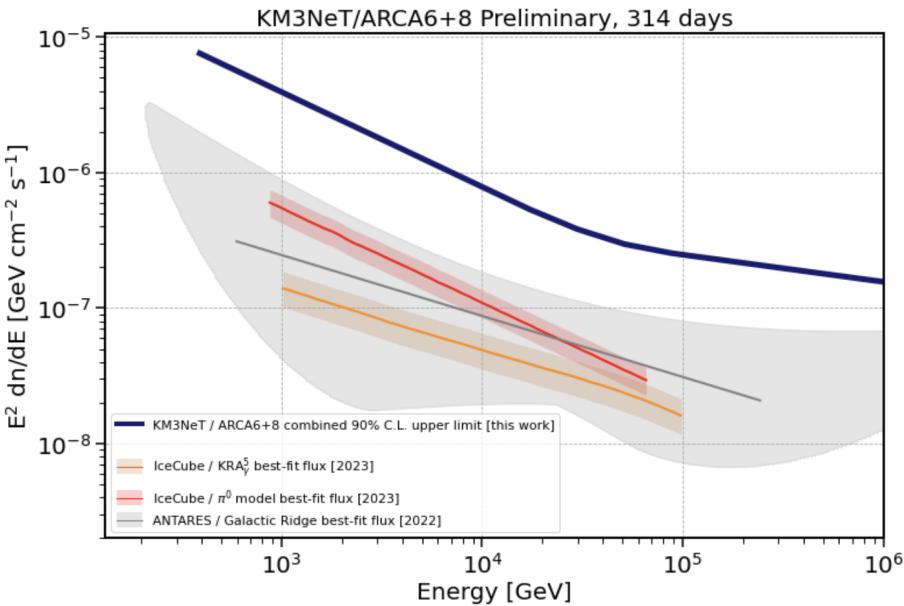


Figure 4: KM3NeT/ARCA6+8 combined 90% C.L. upper limits to a diffuse neutrino emission from the Galactic Ridge, for a range of spectral indices $\Gamma_\nu \in [2.2, 2.7]$. The ANTARES limits and best-fitting flux are also reported (grey shaded area and grey solid line) for the same type of search, derived from [4]. The KM3NeT and ANTARES limits have been integrated over the solid angle, spanned by the Galactic Ridge, to be compared to the best fitting fluxes (red and orange lines) reported by IceCube analysis, which are based on full-sky template method [5].

2.4 Conclusions and outlook

The discovery of a neutrino emission, recently reported by IceCube collaboration, following a hint reported by the ANTARES Collaboration, has opened a new perspective on the possibility to study the properties of our Galaxy through neutrinos [12]. The analysis illustrated in this contribution, searching for a diffuse neutrino flux originated from the Galactic Ridge region, has been performed exploiting data collected by KM3NeT/ARCA with 6 and 8 active detection units, for a total lifetime of 314 days. No excess of events has been found with respect to the background

estimation. Currently the KM3NeT/ARCA detector comprises 21 active detection units, for an effective area which is three times higher than the one of ARCA6/8 and the data gathered with this configuration geometry are currently under analysis. A further expansion of the detector with ~ 10 more detection units is planned for the coming autumn. The limits shown in this work for this type of search are not yet competitive with the results reported by ANTARES and IceCube, but the fast growth planned for the KM3NeT detectors in the near future will allow soon to complement those observations and to further constrain the neutrino emission from the center of our Galaxy. Moreover multi-messenger observations, combining information from gamma-rays observatories like CTA, LHAASO, SWGO and from second generation neutrino telescopes (KM3NeT, GVD, IceCube Gen-2, P-One, TRIDENT) will be fundamental to identify individual sources of CRs and to deeply study the CR properties inside our galaxy.

A. Evaluation of systematic uncertainties

In order to evaluate the systematic uncertainties on the signal acceptance, dedicated Monte Carlo simulations have been performed, allowing to identify a limited number of parameters as the main contributors to the systematic uncertainties. In order to disentangle the different contributions to the overall uncertainty, a dedicated simulation has been produced, in which only one parameter was varied at a time. In Figure 5 the relative difference of the modified Monte Carlo production with respect to the standard one has been calculated in bins of reconstructed neutrino energy. This percentage variation is assumed to be the systematic uncertainty associated with the specific parameter variation. The PMT quantum efficiency has been modified by a 5% (*red dotted line*), while the uncertainty on the water properties are taken into account by modifying the light absorption length by a factor 10%, coherently to what was previously done by ANTARES Collaboration [13] (*green line*). These two different contributions are then summed in quadrature (*blue solid line*) to derive an overall uncertainty, which has been added to the statistical analysis described in section 2.2.

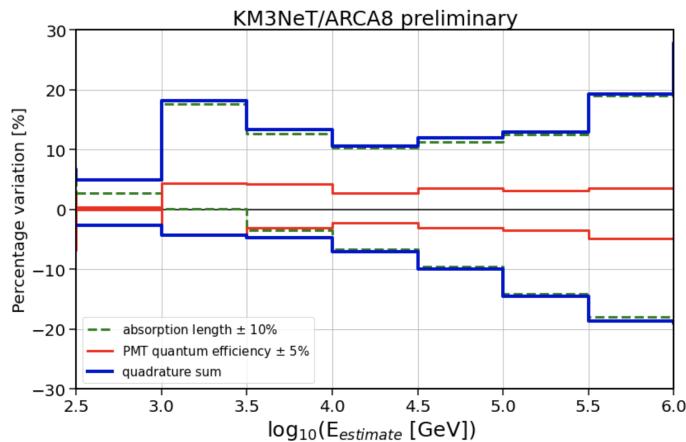


Figure 5: Percentage variation of the modified Monte Carlo simulations, for each parameter modification (specified in the legend) with respect to standard Monte Carlo simulation, as a function of reconstructed neutrino energy.

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