PROCEEDINGS OF SCIENCE

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

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KM3NeT/ARCA is a second-generation neutrino telescope currently under construction in the Mediterranean Sea. Its capability to collect high-quality data has been recently demonstrated by the detection of an ultra-high-energy neutrino of astrophysical origin. Located in the Northern Hemisphere and operating with a high duty cycle, the detector has an optimal view of the Galactic Center, primarily via well-reconstructed track-like events. This study analyses the KM3NeT/ARCA dataset acquired during the detector operation from September 2021 till September 2023 to search for an excess of neutrino events from the Galactic Ridge, defined by Galactic coordinates $|b| < 2^\circ$ and $|l| < 30^\circ$. This region, previously investigated also using ANTARES data, is expected to exhibit a harder spectral index for cosmic ray emission compared to other areas of the Galactic plane.

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1. Introduction

High-energy cosmic neutrinos are able to traverse the Universe largely unaffected (except for redshift and oscillations), hence allowing to probe distant astrophysical objects in a complementary way to cosmic rays and electromagnetic radiation. Being electrically neutral particles, they do not interact with magnetic fields or with the interstellar medium, allowing to trace a direct path back to their source. Neutrinos are expected to be produced in hadronic interactions and around astrophysical sources, through the same mechanisms that are also responsible for a fraction of the observed γ-ray flux. Therefore, neutrino flux predictions can be refined using local CR properties and γ-ray measurements.

The Galactic plane, being the most prominent source in the sky across all electromagnetic wavelengths, is expected to generate neutrinos from the interaction of Galactic cosmic rays with interstellar medium matter located in the centre of our Galaxy or from unresolved sources located along the Galactic plane. In recent years, several theoretical models have been developed to constrain the flux of neutrinos originating from the Galactic plane [1, 2]. Specifically, the predicted neutrino flux is expected to be comparable in magnitude to the diffuse γ-ray flux observed by Fermi-LAT [3]. In the inner region of the Galactic plane, known as the Galactic Ridge ($|l| < 30°$ and $|b| < 2°$ in Galactic coordinates), the cosmic ray spectrum has a harder spectral index than the one measured locally on Earth. This region encompasses the Galactic bar and the innermost parts of the spiral arms, which are responsible for the highest star formation rates in our Galaxy.

In recent years, several studies have reported exciting results on the search for a neutrino flux from the Galactic plane:

- The ANTARES Collaboration found an excess of events originating from the Galactic Ridge that was incompatible with the background-only hypothesis at the 96% confidence level [4];
- The IceCube Collaboration reported the first observation of high-energy neutrinos from the Galactic plane at a significance level of 4.5 σ [5].
- The distribution of arrival directions of public track-like IceCube events with estimated neutrino energies above 200 TeV deviates from the hypothesis of the neutrino flux isotropy, and exhibits a shift toward lower |b|, with a statistical significance of 4.1 σ [6]. Furthermore the same analysis, carried out on Baikal-GVD cascades above 200 TeV, also suggests an excess of neutrinos from low Galactic latitudes [7].

In this contribution the KM3NeT Collaboration reports the results of a new search for a neutrino flux from the Galactic Ridge, using an extended data livetime covering 640 days.

2. The KM3NeT detector

KM3NeT (short for Cubic Kilometre Neutrino Telescope) is a European research infrastructure dedicated to building second-generation multi-km^3 neutrino telescopes [8]. It consists in a network of Cherenkov detectors located on the seabed of the Mediterranean Sea. KM3NeT was designed based on the experience gained from ANTARES, the first-generation neutrino telescope in the Mediterranean, which operated for over 15 years before being dismantled in February 2022 [9].

KM3NeT consists of two primary sites, each aligned with specific physics goals:

- **KM3NeT/ARCA** (Astroparticle Research with Cosmics in the Abyss): located approximately 100 km off the coast of Sicily at a depth of 3500 meters, this detector aims at identifying and characterizing the sources of astrophysical neutrinos. Once fully deployed, it will instrument over one cubic kilometre of seawater.

- **KM3NeT/ORCA** (Oscillation Research with Cosmics in the Abyss): situated about 40 km off the southern coast of France at a depth of 2500 meters, close to the ANTARES deployment site, ORCA focuses on resolving the neutrino mass hierarchy by detecting atmospheric neutrinos. Its final configuration will encompass around 7 megatons of seawater.

Both detectors use the same construction technology, namely a 3-D array of Digital Optical Modules (DOMs) [10] and exploit the same detection principle. The DOM is the active element of the detector, containing 31 3-inch photomultiplier tubes (PMTs). In turn, each Detection Unit (DU) is a vertical, string-like structure anchored to the seabed, carrying 18 DOMs. The key difference lies in the spacing, which is optimized for different neutrino energy ranges: KM3NeT/ORCA in the GeV-few TeV, while KM3NeT/ARCA is tuned to capture fainter astrophysical neutrino fluxes in the TeV-PeV range. Currently, the KM3NeT/ARCA detector consists of 51 DUs, while the KM3NeT /ORCA detector comprises 28 DUs.

3. Dataset

KM3NeT detectors [8], thanks to their modular design, are capable of acquiring data even in the construction phase and with an incomplete detector. During each of the sea campaigns conducted by the KM3NeT Collaboration in the last three years, new DUs have been deployed, producing a great enlargement of the effective area of the KM3NeT/ARCA detector. The telescope acquires data continuously throughout the day, with a duty cycle of more than 95%. Different data taking periods are indicated through the specific number of active DUs.

In this study, the full data sample of the ARCA6, ARCA8, ARCA19 and ARCA21 running periods, after a run based data-quality selection, is analysed:

- **ARCA6** ran from May 2021 through September 2021 for a total of 92 analysed days;
- **ARCA8** from September 2021 through June 2022 for a total of 212 analysed days;
- **ARCA19** from July 2022 to September 2022, for a total of 48 analysed days;
- **ARCA21** from September 2022 to September 2023, for a total of 287 analysed days.

3.1 Event selection

In this contribution, the search for a Galactic cosmic neutrino flux relies on the selection and maximization of the rate of track-like events, generated through ν_μ charged current interaction. For this reason, the event selection is based on the application of series of fixed cuts on reconstructed variables coming out from the track reconstruction algorithm. Trigger-level information, along with variables that indicate the quality of the track fit, are leveraged to filter out noise events. Atmospheric muon events outnumber neutrino interactions by several orders of magnitude. However, their contribution can be significantly reduced by selecting tracks with a reconstructed arrival direction below the horizon. Additional constraints are applied to the likelihood and length of the reconstructed track, as well as to the uncertainty in the reconstructed track direction. This selection serves as a starting point for several analysis within the Collaboration. After this stage to further reduce the background of atmospheric muons, machine learning techniques are applied, specifically a Boosted Decision Tree (BDT). The classifier output score can be seen in Figure 1 for the ARCA21 configuration.

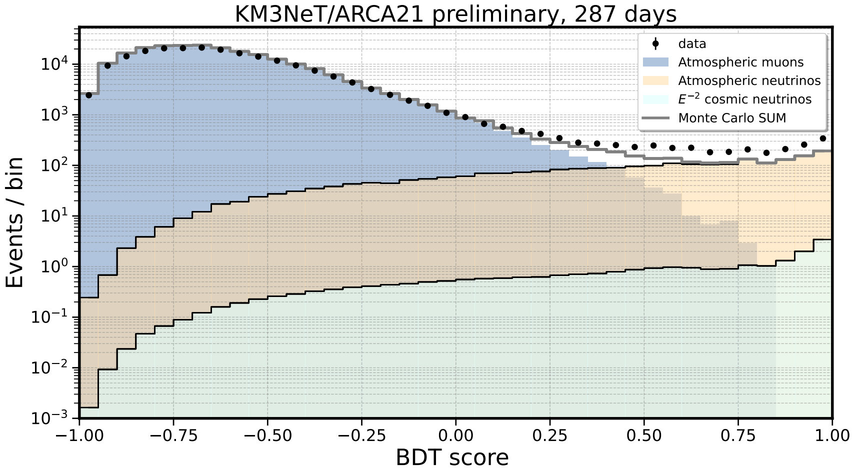

Figure 1: BDT score distributions for the ARCA21 configuration. The plot shows data events (black marks), along with Monte Carlo simulated atmospheric muons (dark blue), atmospheric neutrinos (orange), cosmic neutrino (green) weighted with an E^{-2} flux.

The cosmic neutrino flux is modelled using an unbroken power-law $\frac{dN}{dE} \propto \phi_0 \times E^{-2}$, while atmospheric neutrinos are weighted according to Honda [11] flux for the conventional component and to Enberg [12] flux for the prompt component, with an additional correction to account for the presence of the cosmic ray knee.

4. Method

The objective of the analysis is to assess a potential excess of events coming from the Galactic Ridge and in such a case determine the best-fit values for the signal flux, modelled with an unbroken power-law assumption using the data from ARCA6, ARCA8, ARCA19 and ARCA21. The precise reconstruction of track-like events, with an estimated angular resolution of approximately 0.1° at 100 TeV for the fully deployed detector [13], provides an exceptional opportunity to observe this region of the sky with unprecedented accuracy.

To date, two distinct methodologies have been employed to investigate neutrino emission from the Galactic plane. The first approach relies on template fitting, similar to recent analyses conducted by the IceCube [5] and by ANTARES [14] Collaborations. This method offers the advantage of precisely constraining theoretical models and initial assumptions while fully leveraging the statistical power of likelihood-based techniques. However, it is strongly dependent on the chosen model.

The second approach, initially implemented by ANTARES [4] and subsequently adopted for this analysis by the KM3NeT Collaboration, is a model-independent search. It employs a cut-and-count strategy, comparing the number of detected events and their energy distributions within the region of interest (defined as the ON region) to a data-driven background estimation derived from regions where no signal is expected (OFF regions). To account for the angular resolution of the whole dataset, although the Galactic Ridge is defined as $|b| < 2°$ and $|l| < 30°$, the ON region is defined as $|b| < |b_{reco}|$ and $|l| < |l_{reco}|$, with the values of b_{reco} and l_{reco} determined through an optimization procedure.

An OFF region instead is defined as an area of the sky identical to the ON region in terms of exposure, but shifted in right ascension. For mid-latitude observatories such as KM3NeT, the Earth's rotation allows for the observation of different sky regions with identical detector exposure at different times of the day. The exact value of the time shifts are determined based on the optimized amplitude of the ON region, with the added constraint of avoiding overlap with the Fermi Bubbles.

5. Statistical analysis

A Bayesian binned method, following the one developed in [4], has been exploited for this analysis. The posterior distribution is built starting from the binned likelihood function defined as the product of Poisson probabilities of observing in each energy bin N_i data events, given the expected number of background events B_i and the expected number of signal events $S_i(\phi_0, \gamma)$ computed for a given cosmic flux under a single power-law assumption.

The posterior distribution is then obtained incorporating priors that account for statistical and systematic error on the background and on the signal acceptance. More specifically, Gaussian priors are assumed to account for:

- background statistical uncertainty $\pi(B_i)=Gauss(\mu=B_i,\sigma=\sigma_{B_i})$ with σ_{B_i} corresponding to the statistical error in bin i. Since the final upper limits are extracted from distributions derived from data, no other systematic uncertainties, possibly affecting the background simulation, have been considered;
- signal acceptance $\pi(S_i(\gamma))=Gauss(\mu=1, \sigma=\sigma_{S_i})$ with σ_{S_i} specifically extracted from a systematic evaluation performed through dedicated Monte Carlo productions, and $\pi(\phi_0, \gamma)$ assumed as a flat prior.

The posterior distribution is then marginalized over the nuisance parameters, to derive best-fit values:

$$p(\phi_0, \gamma; N) = \int L(N; S(\gamma), B, \phi_0) \cdot \pi(B_i) \cdot \pi(S_i(\gamma)) \cdot \pi(\phi_0, \gamma) \cdot \prod_i dB_i dS_i(\gamma) \tag{1}$$

Furthermore, sensitivities and *upper limits* (U.L.) to the flux normalization can be derived for a specific spectral index profiling the posterior distribution. This technique is also used to combine different data taking periods, multiplying the posterior probabilities calculated for each detector configuration and computing the marginalized posterior over the total concatenated reconstructed energy bins.

6. Results

Figure 2 shows the final energy distributions for the different KM3NeT/ARCA detector configurations, as obtained after unblinding of the f data sample. Events in the ON region marked as data points are compared to the expected number of events (blue band showing statistical fluctuations). For comparison, also the number of expected signal events, assuming the best-fit flux found in the previous similar search by the ANTARES telescope [4], is reported (red line). In Table 1, the final 90% credible interval upper limits are reported for a range of tested spectral indices.

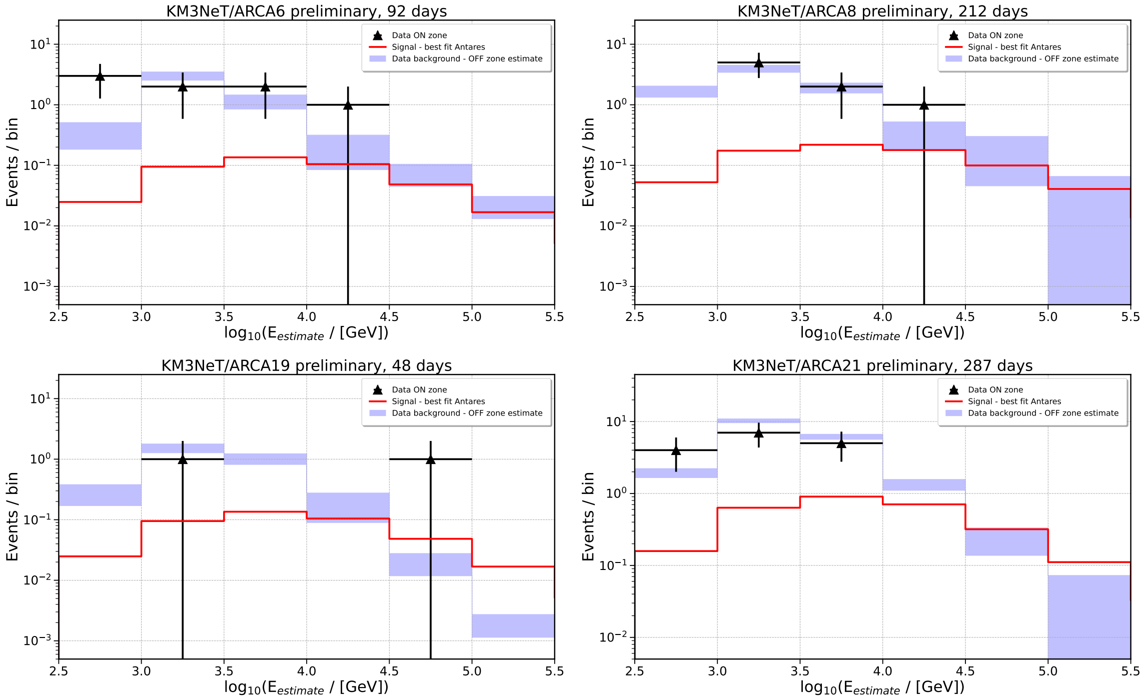
KM3NeT/ARCA6 preliminary, 92 days
KM3NeT/ARCA8 preliminary, 212 days
KM3NeT/ARCA19 preliminary, 48 days
KM3NeT/ARCA21 preliminary, 287 days

Figure 2: Unblinded energy distributions are shown for each KM3NeT/ARCA detector configuration analysed. The ON region data points (black triangles) are compared with the background estimates derived from OFF regions, including the associated relative statistical uncertainty (blue band). The expected number of events, based on the ANTARES best-fit result from this work [4], is also shown as a red line.

7. Conclusion

The detection of a neutrino emission by the IceCube Collaboration, following an earlier indication reported by the ANTARES Collaboration, has opened up new possibilities for studying the properties of our Galaxy through neutrino observations. The analysis presented here focuses on an updated search for a diffuse neutrino flux originating from the Galactic Ridge region, using data collected by KM3NeT/ARCA over a total effective livetime of 640 days. No excess of neutrino events was observed beyond the expected background levels. While the sensitivity achieved in this study is not yet competitive with the results from ANTARES and IceCube, the rapid development of the KM3NeT infrastructure is expected to soon enable complementary observations and tighter constraints on neutrino emissions from the Galactic Center.

90% C.I. upper limits	
Γ_ν	ARCA6+8+19+21
2.2	$1.1 \cdot 10^{-5}$
2.3	$3.3 \cdot 10^{-5}$
2.4	$9.7 \cdot 10^{-5}$
2.5	$2.8 \cdot 10^{-5}$
2.6	$7.7 \cdot 10^{-4}$
2.7	$2.1 \cdot 10^{-3}$

Table 1: 90% C.I. upper limits under a single power-law assumption for a reference energy E_0 = 1 GeV and with spectral indices Γ ranging from 2.2 to 2.7 for the combined data sets. All results are expressed in units of $\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ at a reference energy E_0=1 GeV.

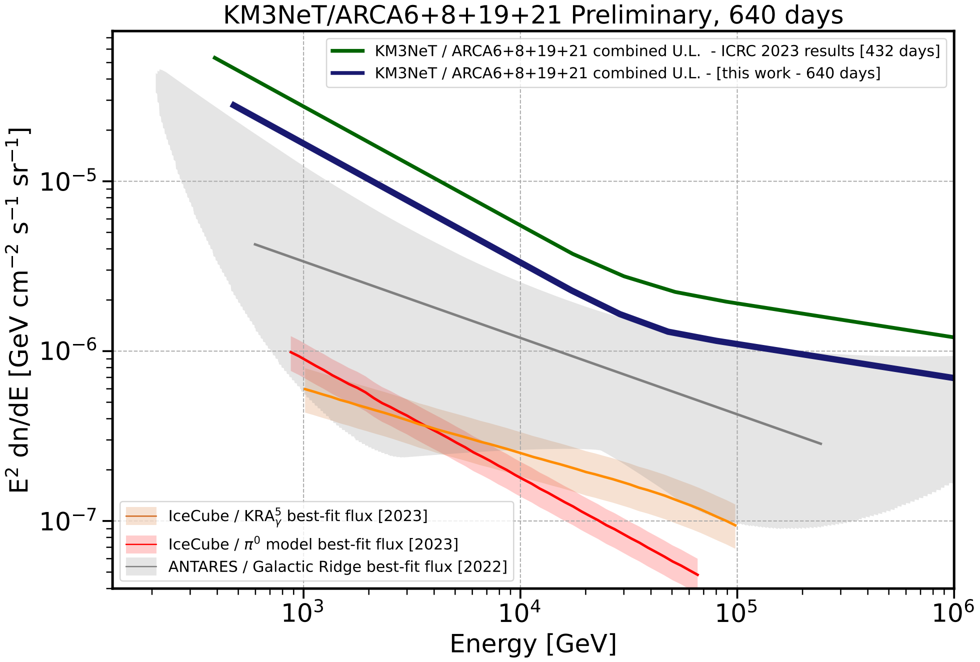

Figure 3: 90% credible interval upper limit (blue solid line) obtained with the full ARCA6+8+19+21 dataset as described in the text is shown for a subset of the tested spectral indices, listed in Table 1 and drawn here as a butterfly contour. For comparison, the best-fit fluxes from ANTARES and IceCube are also included. The IceCube limits have been rescaled to account for the signal fraction within the Galactic Ridge. Results presented at ICRC23 are also reported for comparison [15].

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