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Investigating Neutrino Emission from Gamma-Ray (Galactic) Sources with KM3NeT

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The study of high-energy neutrino emission from astrophysical sources is a key component of multi-messenger astronomy, aiming to uncover the mechanisms of cosmic particle acceleration. Astrophysical sources capable of accelerating cosmic rays to very high energies are expected to produce both neutrino and gamma-ray emissions. Consequently, potential neutrino emissions from known gamma-ray sources can be predicted using theoretical models that relate the expected neutrino spectra to the observed gamma-ray spectra.

In this work, neutrino spectra are estimated for gamma-ray sources listed in the catalogues of experiments such as LHAASO and HAWC. The feasibility of detecting these neutrino emissions is then explored using the KM3NeT/ARCA neutrino telescope, currently under construction in the Mediterranean Sea. KM3NeT/ARCA has already started collecting data with the first installed detection units, and in its final configuration, it will cover approximately a volume of one cubic kilometer of water.

The analysis focuses on: evaluating the performance of the complete KM3NeT/ARCA detector through simulations, and searching for neutrino signals in existing data, corresponding to approximately 640 days of observations. To enhance the sensitivity of this search, techniques such as optimized event selection, tailored to the energy spectra studied by HAWC and LHAASO are employed.

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1. Introduction

High-energy neutrinos and photons are crucial messengers for identifying the sources of cosmic rays. When relativistic protons collide, they produce both charged and neutral mesons. The decays of these mesons yield neutrinos and gamma rays, respectively. However, since high-energy gamma rays can also be produced through inverse Compton scattering by relativistic electrons, the detection of neutrinos provides a clear signature—the so-called "smoking gun"—for the hadronic origin of gamma-rays.

Since the early 2000s, significant progress has been made in the experimental study of these particles. On one side, the construction of gamma-ray observatories such as HAWC [1] and LHAASO [2] enabled measurements at energies of the order of one PeV. On the other hand, experiments capable of detecting high-energy neutrinos were developed. Among these, IceCube has achieved remarkable results, including the detection of a diffuse flux of astrophysical neutrinos and the identification of neutrino events from specific sources such as the blazar TXS 0506+056 [3] and the galaxy Messier 77[4]. It is also worth mentioning the contribution of KM3NeT/ARCA, which has detected the highest energy neutrino observed to date [5].

The KM3NeT/ARCA detector is a neutrino telescope currently under construction at the bottom of the Mediterranean Sea [6]. It consists of a three-dimensional array of optical modules that detect Cherenkov light emitted by the secondary particles produced in neutrino interactions. Once completed, the full detector will comprise 230 detection lines, each equipped with 18 optical modules, instrumenting approximately 1 km^3 of seawater. About 10% of the detector has already been deployed and has begun collecting data.

2. Theoretical Frameworks for the Connection Between Gamma Rays and Neutrinos

As discussed in the previous section, high-energy gamma rays and neutrinos share a common origin in cosmic-ray sources. It is important to highlight that, beyond the experimental perspective, significant theoretical progress has also been made in describing the connection between these messengers.

In 2008, Villante and Vissani [7] proposed a model to estimate the neutrino flux from astrophysical sources. According to their framework, the neutrino flux can be derived from the measured gamma-ray flux. Assuming a hadronic scenario, the production rates of mesons—whose decays generate both neutrinos and gamma rays—can be theoretically linked at the production site.

The model was later refined by Mascaretti and Vissani through the inclusion of the most recent neutrino oscillation parameters [8].

A key advantage of this approach lies in its conceptual and computational simplicity. It does not require detailed parameterizations of gamma-ray observations, making it applicable to sources with measured spectra, such as those studied by HAWC and LHAASO.

It is essential to note that the model uses the intrinsic (i.e., at-source) gamma-ray flux to estimate the corresponding neutrino emission. However, the gamma-ray flux reported by experiments generally refers to the observed flux, which may differ from the source flux due to attenuation effects.

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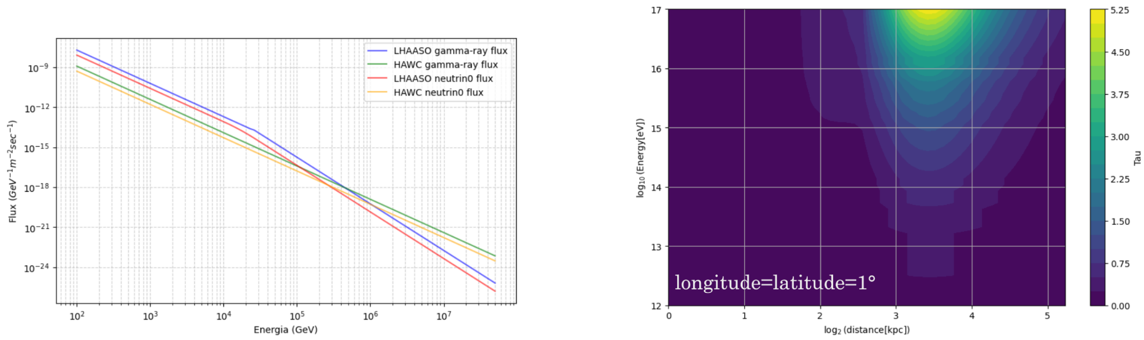
High-energy gamma rays traveling from the source can interact with cosmic background photons—such as those from the Cosmic Microwave Background (CMB) and the Interstellar Radiation Field (ISRF)—leading through a pair-production mechanism. For such a process, attenuation (expressed as $e^{-\tau_{\gamma\gamma}}$) can be characterized and can be modeled numerically, as described by Lipari and Vernetto[9]. And the flux at the production site can be estimated as the ratio between the observed(measuered) gamma ray flux the attenuation factor (expressed as $e^{-\tau_{\gamma\gamma}}$) following the law of radiative transport.

For an istance in figure 1a two neutrino fluxes are reported, the redline is the one estimated from two gamma-ray flux expression which LHAASO used to fit the source spectra [2], the orange one is estimated assuming HAWC gamma-ray spectrum fit expression. In figure 1b the distribution of the optical depth $\tau_{\gamma\gamma}$, computed using the Lipari-Vernetto parameterization, is reported with respect to the energy and to the distance between the source and the hypothetical observer for a fixed position.



(a) **(b)**

Figure 1: Figure a) Gamma-ray and neutrino fluxes as a function of the energy. b) Optical depth $\tau_{\gamma\gamma}$ distribution respect to energy and distance for a fixed position (latitude=longitude=1°).

3. KM3NeT/ARCA: Data Samples and MC Productions

The theoretical framework described above allows us to estimate the expected neutrino flux from astrophysical sources. Based on these expectations, it is possible to analyze the data collected by KM3NeT/ARCA to search for a potential signal.

For KM3NeT/ARCA, each data set corresponds to a distinct detector configuration and dedicated event selection, ensuring no overlap between events. The datasets used in this analysis include:

- **ARCA6tracks**: KM3NeT/ARCA period with 6 active detection lines (92 days).
- **ARCA8tracks**: KM3NeT/ARCA period with 8 active detection lines (212 days).
- **ARCA19tracks**: KM3NeT/ARCA period with 19 active detection lines (48.4 days).
- **ARCA21tracks**: KM3NeT/ARCA period with 21 active detection lines (287.4 days).

In addition to the collected data, the theoretical methods previously discussed can also be applied to the full detector configuration, using the most up-to-date detector performance parameters from simulations.

4. Analysis Method

4.1 Candidate Source List

For this study, sources were selected from the first LHAASO catalog [2] and the third HAWC catalog [1]. Both catalogs provide spectral fits for the observed sources, though they adopt different parametrizations: HAWC reports spectra as single power laws over the entire energy range, while LHAASO uses a broken power law, reflecting the use of two sub-detectors—the WCDA and KM2A—optimized for energy ranges below and above 25 TeV, respectively.

Tables 1 and 2 list the selected sources from each catalog. For each source, the expected neutrino flux was estimated in two scenarios:

- using the Mascaretti–Vissani formula, assuming no gamma-ray attenuation;
- applying the attenuation factor computed using the Lipari–Vernetto method, and incorporating this correction into the Mascaretti–Vissani formula, as described in Section 2.

4.2 Signal and Background Modeling, and Likelihood Framework

To assess the compatibility of the observed data with the expected neutrino signal from candidate sources, a binned likelihood method is employed. This procedure, developed for KM3NeT point-source analyses [10, 11], uses a test statistic λ defined as the logarithm of the likelihood ratio between the signal-plus-background and background-only hypotheses:

$$\lambda = \log L(\mu = \widehat{\mu}) - \log L(\mu = 0) \tag{1}$$

The likelihood function is defined as:

$$\log L(\mu) = \sum_{\text{bins}} \log(B_i + \mu S_i) - (B_i + \mu S_i) \tag{2}$$

where S_i is the expected number of signal events in bin i, obtained by convolving the predicted neutrino flux with the detector's effective area. The background histogram B_i is estimated either from data using a data-driven technique (as described in Ref. [11]), or from Monte Carlo simulations for projections involving the full detector configuration [10]. The signal strength (μ) is varied to obtain test statistic distributions for statistical analysis. For a fixed value of the signal strength ($\widehat{\mu}$), pseudo-experiments (PE) are generated by randomly drawing each N_i from a Poisson distribution with mean $B_i + \widehat{\mu} S_i$.

#	Source Name	RA (°)	Decl (°)	width (°)	Association (°)
1	1LHAASOJ1809-1918u	272.38	-19.3	0	HESSJ1809-193(0.24)
2	1LHAASOJ1814-1719u*	273.27	-17.89	0	2HWCJ1814-173(0.16)
3	1LHAASOJ1825-1418	276.25	-14	0.81	HESSJ1825-137(0.56)
4	1LHAASOJ1825-1337u	276.45	-13.63	0	HESSJ1825-137(0.15)
5	1LHAASOJ1825-1256u	276.44	-12.94	0	HESSJ1826-130(0.14)
6	1LHAASOJ1813-1245	273.36	-12.75	0.31	HESSJ1813-126(0.07)
7	1LHAASOJ1831-1007u*	277.81	-9.83	0	HESSJ1831-098(0.25)
8	1LHAASOJ1834-0831	278.44	-8.38	0.4	HESSJ1834-087(0.24)
9	1LHAASOJ1837-0654u	279.31	-6.86	0.33	HESSJ1837-069(0.05)
10	1LHAASOJ1839-0548u	279.79	-5.81	0.22	LHAASOJ1839-0545(0.17)
11	1LHAASOJ1841-0519	280.21	-5.23	0.62	HESSJ1841-055(0.25)
12	1LHAASOJ1843-0335u	280.91	-3.6	0.36	HESSJ1843-033(0.06)
13	1LHAASOJ1848-0153u	282.02	-1.78	0.56	HESSJ1848-018(0.11)
14	1LHAASOJ1850-0004u*	282.89	-0.07	0.21	HESSJ1852-000(0.36)
15	1LHAASOJ1852+0050u*	283.10	0.84	0.85	2HWCJ1852+013*(0.55)
16	1LHAASOJ1857+0203u	284.38	2.06	0.28	HESSJ1858+020(0.21)
17	1LHAASOJ1910+0516*	287.55	5.28	0.3	SS433w1(0.26)
18	1LHAASOJ1908+0615u	287.05	6.26	0.36	MGROJ1908+06(0.07)
19	1LHAASOJ1912+1014u	288.38	10.5	0.5	HESSJ1912+101(0.10)
20	1LHAASOJ1914+1150u	288.73	11.84	0.21	2HWCJ1914+117*(0.13)
21	1LHAASOJ0703+1405	105.83	14.1	1.88	HWCJ0700+143(0.72)
22	1LHAASOJ1922+140	290.73	14.11	0.1	W51(0.13)
23	1LHAASOJ0634+1741u	98.57	17.69	0.89	Geminga(0.54)
24	1LHAASOJ0534+2200u	83.61	22.036	0	Crab(0.01)
25	1LHAASOJ0542+2311u	85.71	23.2	0.98	HAWCJ0543+233(0.21)
26	1LHAASOJ0622+3754	95.5	37.9	0.46	LHAASOJ0621+3755(0.03)

Table 1: List of selected sources from the LHAASO catalogue [2]; for each source, the coordinates (right ascension RA and declination Decl) are reported as well as the estimated extension/width and the associated source (with the distance)

#	Source Name	RA (°)	Decl (°)	width (°)	Association
1	3HWCJ1757-240	269.30	-24.09	1.00	HESSJ1800-240B
2	3HWCJ1803-211	270.97	-21.18	0.00	HESSJ1804-216
3	3HWCJ1849+001	282.35	0.15	0.00	IGRJ18490-0000
4	3HWCJ1857+027	284.33	2.80	0.00	HESSJ1857+026
5	3HWCJ0634+067	98.66	6.73	0.50	HAWCJ0635+070
6	3HWCJ0617+224	94.39	22.47	0.00	IC443

Table 2: List of selected sources from the 3rd HAWC catalogue [1]; for each source, the coordinates (right ascension RA and declination Decl) are reported as well as the estimated extension/width and the associated source (with the distance).

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5. Results

5.1 Results for available data

Using the likelihood method described above, the available DATA were analyzed to search for a signal compatible with the theoretical assumptions. However, since no evidence of such signal was found, the flux upper-limit was computed for each of the sources in fig2a. For each source, also the enrgy range where 90% of the signal is expected are estimeted in fig2b (sources from the LHAASO catalogue) and in fig2c (sources from the LHAASO catalogue). Looking at the upper limits the best three LHAASO sources are J1825-1418, J1814-1719u* and J1825-1337, while from the HAWC catalogue the best values are optained for J1849+001, J1857+027 and J1803-211. From the ratio plot in figure in 2a the gamma-ray absorption seems to impact the results less than 10 % for most of the considered sources except for the HAWCJ1849+001, where the difference between the upper limits computed with the absorption correction and the one without the correction is 25%.

5.2 Full detector performance

For the full detector, the 3σ discovery potential was computed as a function of time to estimate the time for a 3σ obesrvation. As shown in figure 3, in 5 years KM3NeT/ARCA230 will be able to make a 3σ observation for 5 sources, for 10 sources in 10 years and for 16 sources in 20 years of observation.

6. Conclusions

In this work, the information from gamma-ray observatories was used to estimate the neutrino flux from astrophysical sources. A compatibility for such neutrino signal was checked in the first DATA collected by KM3NeT/ARCA. No significant signal excess was found. However, the study, with the simulation of the final configuration of the detector, shows that once KM3NeT/ARCA230 is completed, it will be able to observe this signal for many of the sources with a significance of at least 3 sigma.

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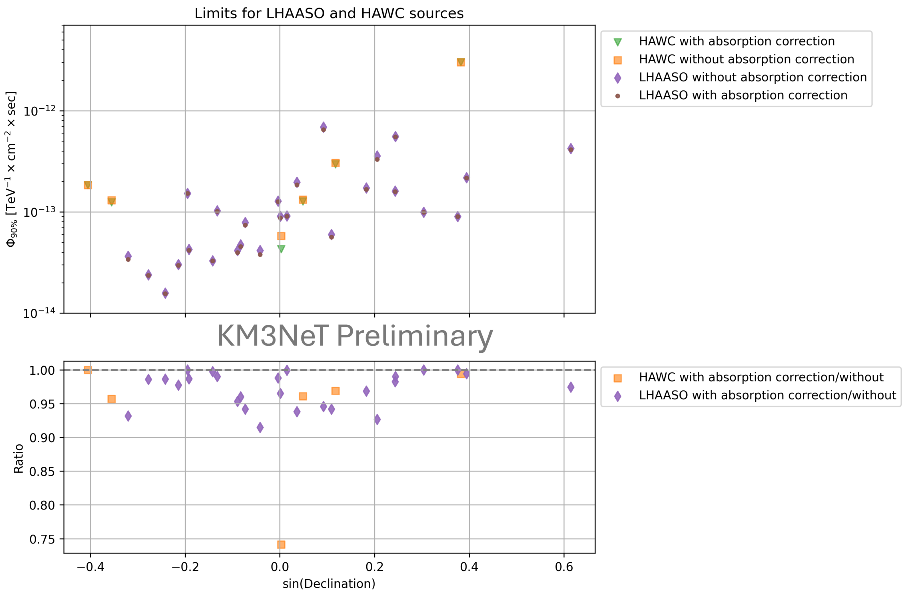

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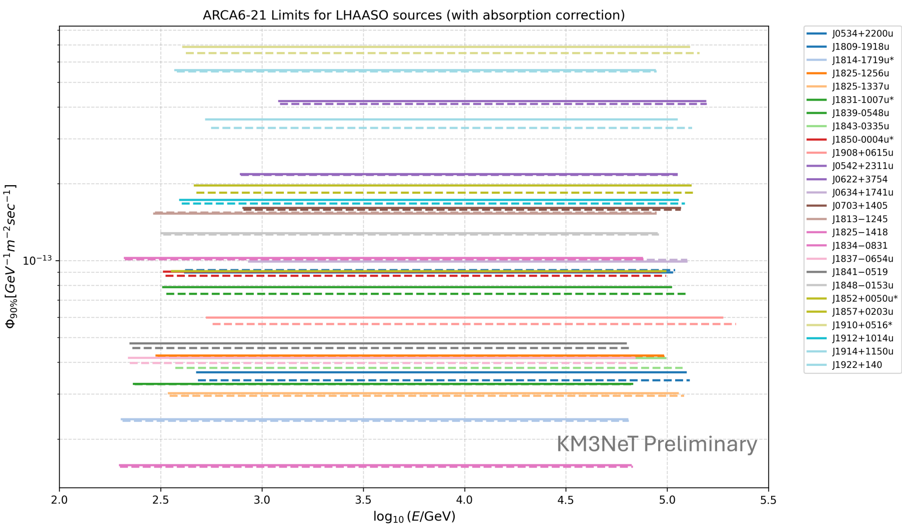

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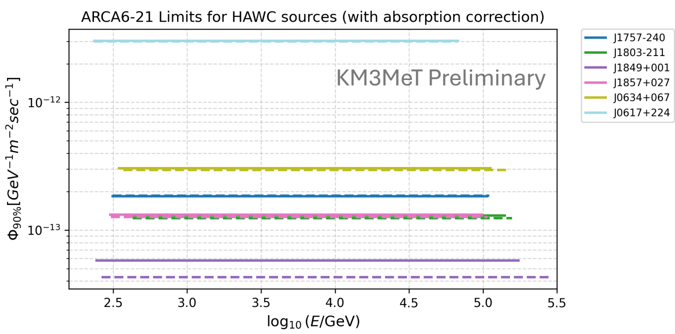

(c)

Figure 2: A) The flux upper limits for each considered sources, reported as a function of the sine of the declination. B-C) the flux upper plotted for the energy range, where 90% of the signal is expected for LHAASO sources (plot B) and HAWC sources (plot C)

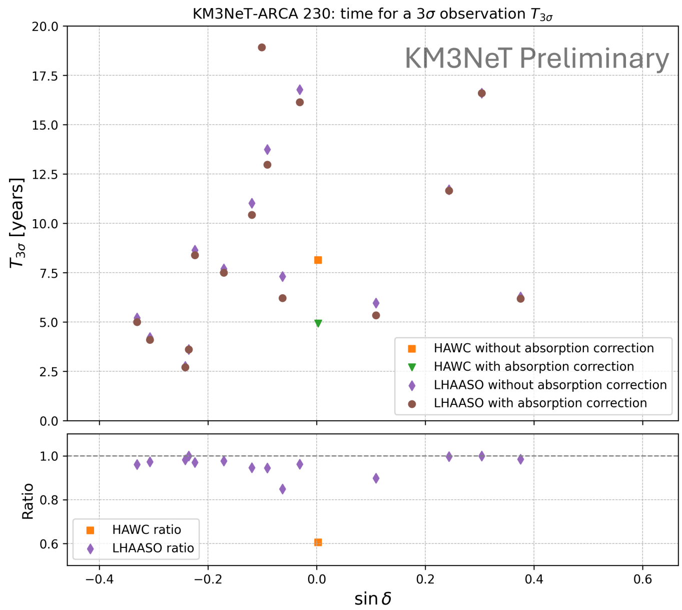

Figure 3: Time for a 3σ observation for each considered sources, reported as a function of the sine of the declination.

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