Time-integrated search for astrophysical neutrino emission with 2 years of KM3NeT/ARCA data

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Abstract

The **identification of cosmic objects emitting high energy (HE) neutrinos (ν)** provides new insights about the Universe and its active sources. **KM3NeT/ARCA data** from May 2021 taken with an evolving detector geometry up to 21 detection units is used. Data up to December 2022 is unblinded for the point source study. After the **event selection** the **detector response** is determined and used for the **binned likelihood analysis** in order to look for a neutrino excess from 101 preselected **candidate sources** assuming an $E^{-\gamma}$ spectrum. No strong neutrino emitters are found for $\gamma = 2.0, 2.5,$ or 3.2. The lowest pre-trial p-value (0.011) was found for the **AGN J1512-0905** for $\gamma = 2.0$, but this is in line with the background expectation. With the additionally available data for ARCA21 up to September 2023, the sensitivity is estimated to **improve** by a factor 2.

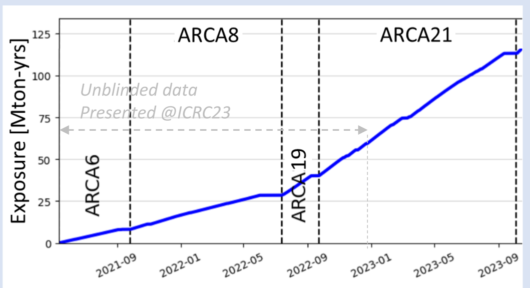
ν detection KM3NeT/ARCA

Detector [1]

- At the bottom of the Mediterranean Sea in Italy, KM3NeT/ARCA is sensitive to GeV – PeV neutrinos. In its full configuration it will consist of two 'building blocks', 115 vertical lines each, with 18 light sensitive elements per line to detect Cherenkov radiation caused by charged particles produced in ν interactions. Currently KM3NeT/ARCA is taking data with 28 lines

Dataset

- The analysis uses data from a period when KM3NeT/ARCA was taking data with 6 – 21 lines between May '21, and Sept '23
- Data till Dec '23 is unblinded. This work provides a new sensitivity estimate for when the full ARCA21 dataset till Sept'23 would be used



Event topologies

- Track: High energy μ from ν_μ^{CC} interactions, ν_τ^{CC} τ-decays or directly from the atmosphere, traveling trough water before it decays. Provides good pointing resolution
- Shower: Electromagnetic/Hadronic shower from NC and ν_e^{CC} interactions. Provides good energy resolution

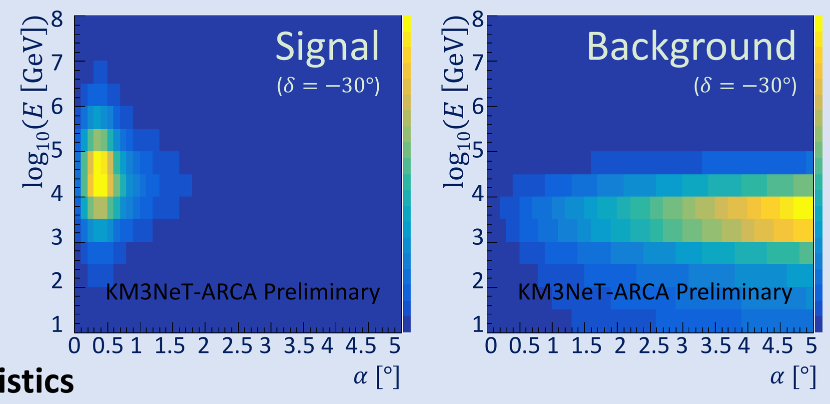
Background sources

- Atmospheric neutrinos (prompt & conventional) and muons
- Bioluminescence and K40 decay

Analysis method

Binned likelihood

- Performed in 2D: the angular distance of the event to a source: α [°] {0 - 5} and the energy of the event: $\log_{10}(E$ [GeV]) {1 - 8}
- H0 (background only), and H1 (signal + background) models are built from the signal and background expectations. (Scaled up) simulations are used for the signal modelling, and scrambled data is used for the background modelling. The figure shows example distributions for a source at $\delta = -30$ in the ARCA21 period
- The signal strength is kept as a free parameter



Statistics

- The log-likelihood is the Poisson probability of the bin-contents (i):

$$\log(L) = \sum_{i}^{N_{\text{bins}}} N_i \log(B_i + \mu S_i) - B_i - \mu S_i$$

Where N_i is the number of events in data in bin i, and μ is the signal strength, which effectively parameterises the flux intensity

- The test statistic is defined as: $\lambda = \log(L(\mu = \hat{\mu})) - \log(L(\mu = 0))$

Event selection

Aim

- Provide sample of well reconstructed tracks coming from up-going or horizontal ν's interacting inside or in the vicinity of KM3NeT/ARCA
- Since the analysis method does not require a-priori optimisation of the signal to background ratio, but will perform best with as much signal as possible, the event-selection criteria are quite loose keeping the signal efficiency high

Signal definition

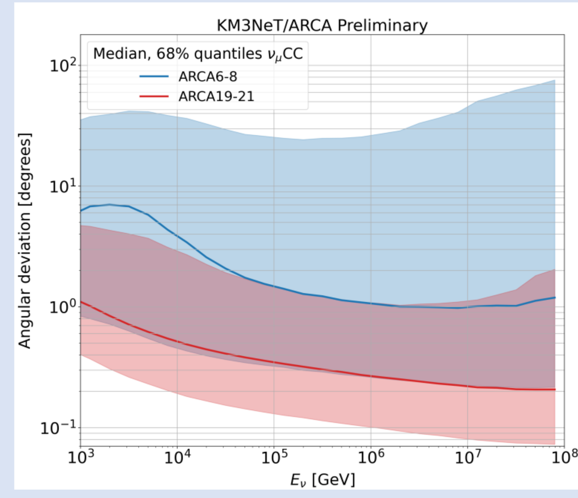
- A cosmic neutrino with an outgoing muon

Selection criteria

- Select horizontal / upgoing tracks ($\cos(\theta) > -0.1$)
- Select events with high number of hits used in the reconstruction
- Select events with good fit quality (based on the likelihood of the reconstruction)
- Boosted decision tree

Detector response

- Detector response functions are used to determine the expected signal expectation, among which the angular resolution as function of the E_ν for ν_μ^{CC} events.



The median angular uncertainty improves with the growing detector.

Energy integrated median angular resolutions:

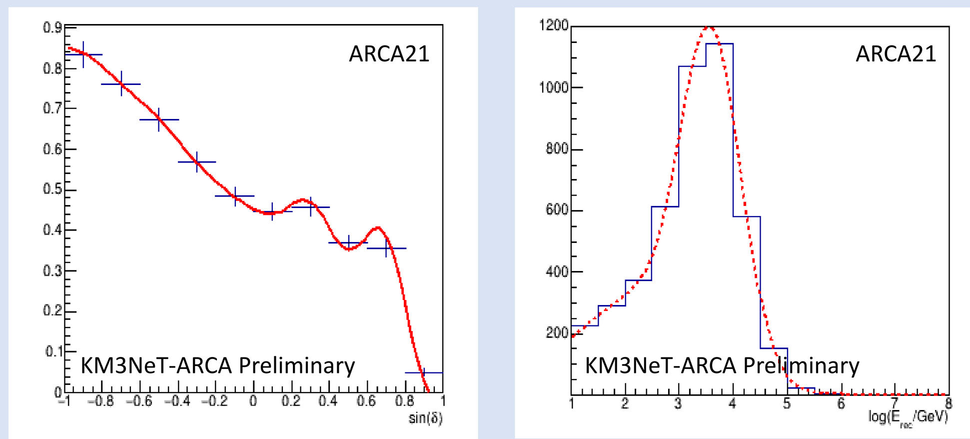
ARCA6	2.11°
ARCA8	1.56°
ARCA19	0.37°
ARCA 21	0.38°

* The plot and table are based on simulation produced alongside the data until December '22

The full KM3NeT/ARCA230 detector will achieve $< 0.1°$ for $E_{\nu_\mu} > 30$ TeV

Background estimation

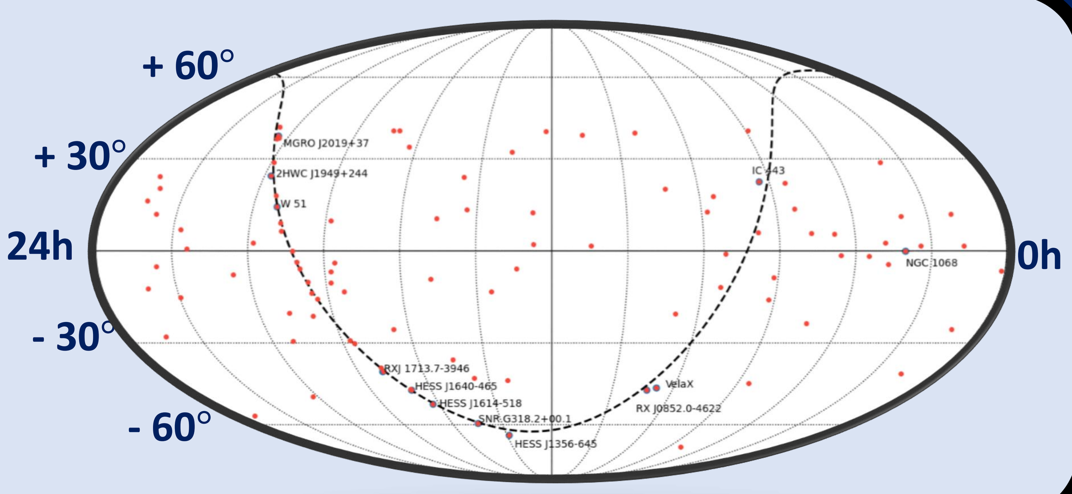
- For each considered period, the background expectation is determined based on scrambled data. A spline to the $\sin(\delta)$ distribution is used, and a double, or triple Gaussian fit to the $\log_{10}(E$ [GeV]). Example distributions for the ARCA21 full period are shown:



Candidate sources

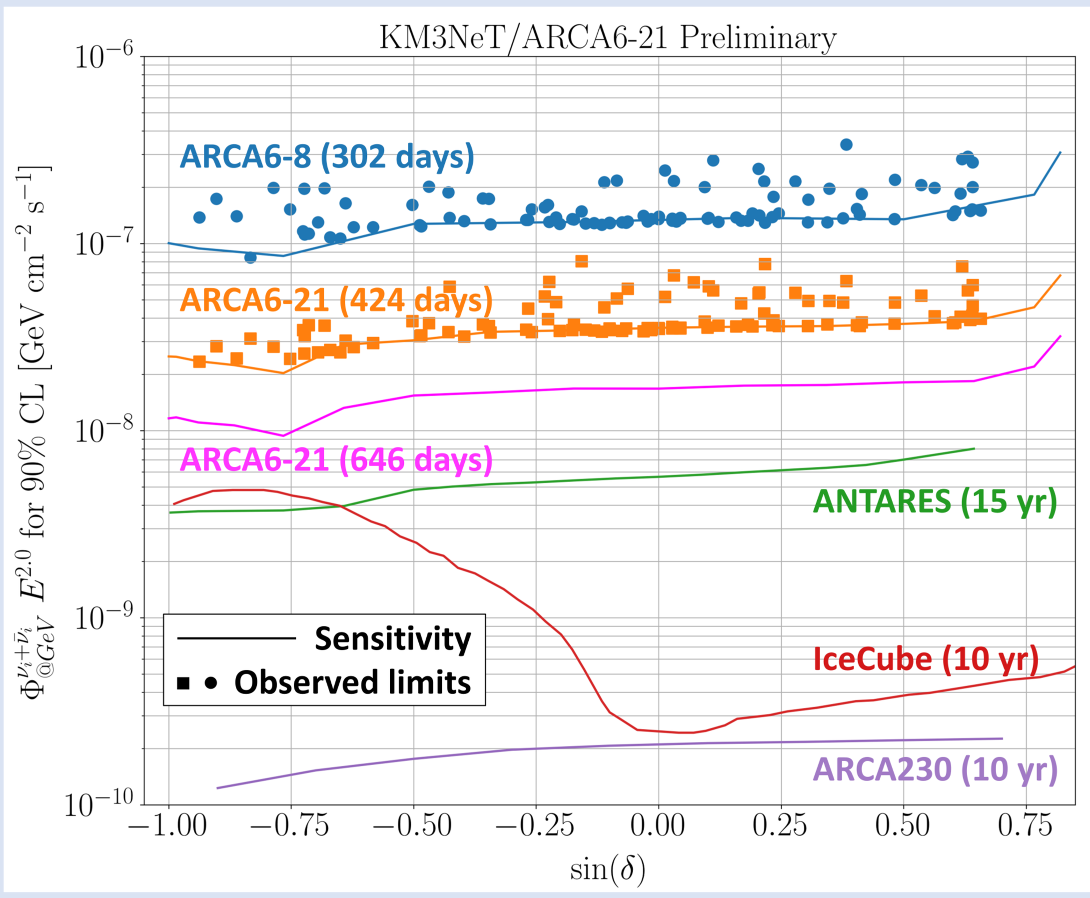
The sources

- The analysis probes 101 candidate sources selected for various reasons [5 – 15]
- 12 sources are known to be spatially extended in the sky. For these sources the detector point spread function is modified with a Gaussian or disk-like smearing around the source centre in line with the source size
- An $E^{-\gamma}$ spectrum is tested for each source, for $\gamma = 2.0, 2.5$ and 3.2
- Candidate sources are visualized in the sky map in equatorial coordinates. Extended sources are labelled by their name



Result

The plot shows for growing KM3NeT/ARCA detector configurations in comparison with other telescopes: the sensitivities as a function of $\sin(\delta)$ and the observed limits on the flux for the individual candidate sources, assuming an E^{-2} energy spectrum.



No strong neutrino emitter found

- No strong neutrino emitters are found among the preselected candidate sources for all checked spectra: $\gamma = 2.0, 2.5,$ or 3.2. Since no significant detection is made, upper limits are set on the flux for each source.
- For the ARCA6-21 (424 days) unblinded dataset, the lowest pre-trial p-value (0.011) was found for the AGN J1512-0905 at at RA = 228.21°, δ = −9.10°, for $\gamma = 2.0$, but with a candidate list of ~100 sources, this is in line with the background expectation.

Quickly improving sensitivity

- With the additionally available data for ARCA21 up to September 2023, (i.e. the ARCA6-21 (646 days) dataset), the sensitivity is estimated to improve by a factor 2.

Conclusion

- This study shows that among the followed up sources, there were no strong neutrino emitters in the unblinded KM3NeT/ARCA period of May 2021 – September 2022. The sensitivity of the KM3NeT/ARCA detector is fastly increasing

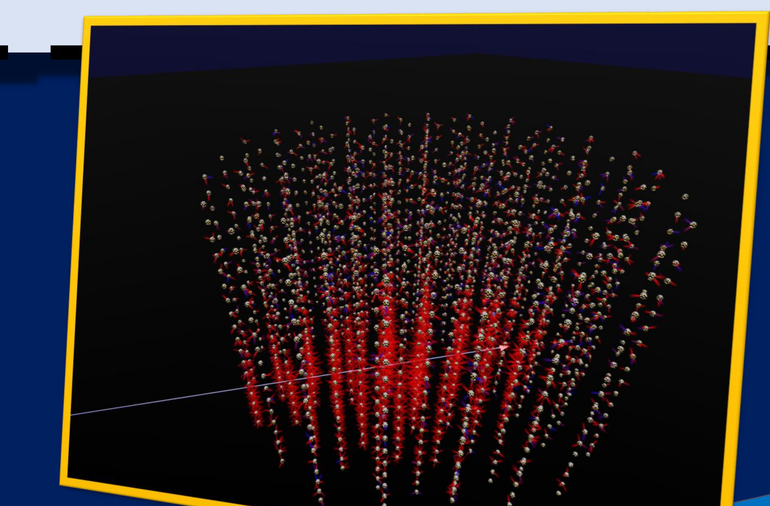
Next steps

1: Perform an analysis with more data!

- Very soon ARCA21 data will be unblinded
- Eight months of ARCA28 available data will be processed and added as well
- Deploy more lines (to be foreseen this autumn!)
- Perform combined analysis with ANTARES
- Do an all sky search without preselecting source candidates

2: Expand current Monte-Carlo based work

- Include shower channel
- Fine tune analysis methods:
  - Automate steps for future analysis



Take Home Message

Neutrino emission is searched among 101 known candidate neutrino point sources among which 12 extended sources. No strong neutrino emitters were observed between May 2021 and September 2022. The lowest pre-trial p-value (0.011) was found for the AGN J1512-0905, but this observation is in line with the background expectation. Nevertheless this study shows that our analysis framework is in place, and working. While our detector is taking more data, work is ongoing to expand the framework in order to improve our performance and do more extended studies. Soon the full available ARCA21 dataset will be unblinded. Furthermore, there are already and additionally available 8 months of data taking with ARCA28, and new deployments are foreseen in autumn this year, increasing the potential of exploring cosmic neutrino emitters.

References

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[2] See ICRC contribution: poster 928 by R.Muller on behalf of the KM3NeT collaboration, https://indico.desy.de/event/27991/contributions/101486/
[3] See ICRC contribution: poster 1142 by G.Illuminati on behalf of the ANTARES collaboration, https://indico.desy.de/event/27991/contributions/101388.
[4] IceCube Collaboration. (2017). Astroph. J. 835, 151.
References for selected candidate sources: [5] https://arxiv.org/pdf/1910.08488.pdf | [6] https://pos.sissa.it/395/1161/pdf | [7] https://arxiv.org/pdf/2012.15082.pdf | [8] https://iopscience.iop.org/article/10.1088/1748-0221/16/10/C10005/meta | [9] https://arxiv.org/abs/2103.15526 | [10] Alexander Plavin | [11] https://www.nature.com/articles/s41586-021-03498-z & https://pos.sissa.it/395/1161/pdf | [12] IC211208A, GVD211208A, Baksan | [13] IC220205B | [14] IC220225A | [15] IC220304A

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