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Open-Science Integration of a Combined Analysis of KM3NeT and CTA into the EOSC Infrastructure

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KM3NeT is deep-sea neutrino research infrastructure in the Mediterranean Sea, including a cubic kilometer neutrino underwater telescope. The construction and commissioning of the detector infrastructure is currently underway. The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. Both collaborations contributed to ESCAPE, the European Science Cluster of Astronomy and Particle Physics, which brings together many astrophysics and particle physics experiments to further open science in the community via the European Open Science Cloud (EOSC). The data, measured as individual events in both telescopes, motivates the use of common tools for analysis. In the multi-messenger era, investigation of a specific scientific question from different experiments in a synergic approach yields significant additional insights not achievable with information from one messenger alone. This approach was successfully employed in a combination of simulated data from the high-energy array of KM3NeT (ARCA) and CTA to distinguish between leptonic and hadronic emission scenarios of gamma-ray sources in the Milky Way using a common software framework. This contribution demonstrates the successful deployment of the analysis into the EOSC/ESCAPE thematic cluster infrastructure for future usage in the open science regime.

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1. Introduction

Modern astrophysical experiments lead us into a new era of computational analysis. More and more computing resources are required that in turn make a single-user analysis very inefficient. Open science helps to address this problem following the FAIR principles [1]. This strategy is realized in EOSC [2], where a virtual research environment was implemented for a user with access to data and software across borders and scientific disciplines. Several scientific clusters contributed to EOSC, one of them *ESCAPE* [1] with focus on astrophysics and particle physics experiments. Two test scientific projects (TSP) were proposed in the ESCAPE framework: one on dark matter and one on the astrophysics of the extreme universe. The combined analysis for distinguishing between leptonic and hadronic emission scenarios for galactic gamma-ray sources using KM3NeT and CTA data was performed as joint research of both collaborations [3]. As shown here, this analyses was successfully publicly released as an example for the extreme universe TSP.

2. Description of the analysis

Combined analyses of data from the CTA [4] and the KM3NeT neutrino telescope [5] offers a powerful approach to unravel the mysteries of astrophysical phenomena. By integrating information from very-high energy (VHE) gamma rays, measured by CTA, and neutrinos detected by KM3NeT, scientists can gain a more comprehensive understanding of a single object in the Galaxy. This combination provides a more complete picture of these astrophysical sources, enabling researchers to investigate their physical properties, including emission processes and source characteristics. This unique synergy between CTA and KM3NeT enhances the sensitivity to different emission models, making the study of galactic objects even more insightful and promising.

There are two possible options for the emission of VHE gamma rays from distant galactic sources: leptonic and hadronic scenarios. In the hadronic case, gamma rays are produced mainly due to pion decays (PD) with the release of a significant amount of neutrinos. On the contrary, leptonic emission through the inverse Compton interaction (IC) entails the absence of neutrinos in final states. Thus, the possible observation of neutrinos plays a key role in determining the origin of gamma rays. The open-source python package `gammapy` [6] is for gamma-ray astronomy and a core library for the science analysis tools of CTA. In Ref. [3] a first attempt was made to adapt the Monte-Carlo KM3NeT neutrino data to `gammapy` in a consistent way to CTA data. For the combined analysis, the following gamma-ray sources were considered: Vela X, RX J1713.7–3946, Westerlund 1, and eHWC J1907+063.

The analysis in Ref. [3] consists of the following steps:

- Creation of the KM3NeT instrument response functions (IRF) compatible with `gammapy`. The IRFs are based on the original Monte-Carlo pseudo-data generated using the official KM3NeT software.
- Adding the CTA IRF that is publicly available.
- Generating models of gamma-ray and neutrino input fluxes for selected sources based on real gamma-ray observations.

[1] https://projectescape.eu

- Creation of neutrino and gamma-ray pseudo-datasets based on Poisson randomized events.
- Performing of a binned likelihood analysis.
- Creation of summary plots of the results.

3. Scientific repository

The combined analysis was released for public usage in the KM3NeT github repository [2] and also mirrored in the ESCAPE VRE github repository [3]. The repository is also published on Zenodo [7]. It offers the user the ability to reproduce all scientific results of the original paper [3]. This can be achieved locally by creating a work environment that is based on `gammapy v0.17` and `python 3.8`. Besides this, it supports several ways of remote execution, which will be highlighted later. The repository contains all the necessary folders and files to run the analysis. A distinctive feature of the analysis itself is the presence of both IRFs for CTA and KM3NeT in the standard representation for `gammapy`. According to this the IRF includes next parts:

- *Effective area* represents the hypothetical observable area for an incoming particle as a function of energy and its direction.
- *Energy dispersion* is responsible for the imperfection of energy reconstruction and allows us to take this into account.
- *Point spread function* describes how the instrument will image a point source and deviates from the ideal case.
- *Background* is the rate of incoming particles for the chosen direction and energy window.

3.1 Integration with EOSC/ESCAPE infrastructure

The repository with the combined analysis can be executed remotely including the heavy computationally part dedicated to the Maximum Likelihood Scan, which is difficult to run locally. One option for remote execution is realised through the VRE platform [9]. Once ESCAPE credentials are obtained, the user is able to log into the Jupyterhub VRE notebook service and select an environment for the combined analysis. All notebooks can be executed within this environment.

Another option is to use a reproducible analysis platform, e.g. REANA [4]. The main advantage of REANA is its simplicity and the necessity to provide only one yaml-file that defines the configuration of the executed analysis. For this purpose, there is a folder `reana` in the `analysis` directory. It has several yaml-files and python scripts. Each yaml-file is dedicated to a specific part of the analysis. These scripts will be launched on the REANA server. It should be noted that the combined analysis with REANA can be carried out not only on ESCAPE servers, but also on any other servers with REANA installed.

[2] https://github.com/KM3NeT/Analysis-galactic-sources-CTA-KM3NeT

[3] https://github.com/vre-hub

[4] https://github.com/reanahub

4. Conclusion

The successful deployment of the combined analysis inside the EOSC/ESCAPE infrastructure is a pioneering step by the KM3NeT collaboration to popularize the concept of open science in astroparticle physics and provide a working example of the form future research might take. It adds to the significance and validity of the research in comparison with traditional publications. Moreover, provenance and reproducibility will be simplified for newcomers in this research topic.

5. Acknowledgements

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