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On the possibility to measure galactic photons at the altitude of the Pierre Auger Observatory

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The presence of galactic sources displaying a power-law dependence in their gamma-ray fluxes has been recently reported by gamma-ray observatories such as LHAASO and HAWC. This exciting discovery, with a few sources showing no cutoff in their flux, has the potential to enable measurements of photon fluxes at energies even higher than 10^{15} eV. To measure the tails of the energy spectra of these sources, we investigate the capabilities of a new dense array of water-Cherenkov detectors, the Project for Extreme PeVatron Sources (PEPS). To distinguish primary photons from the overwhelming cosmic-rays background, we investigate the performance of a detector that optically divides the water volume to separate the muonic component of air showers from the electromagnetic one. The expected sensitivity of these layered surface detectors, covering a 2 km^2 area at the site of the Pierre Auger Observatory, is presented. With the potential to make groundbreaking discoveries, such an array might represent a promising area of research in gamma-ray astronomy.

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1. Introduction

Gamma-ray astrophysics has reached a new era with the discovery of sources that produce photons with energies above 10^{15} eV by the LHAASO [1] and HAWC [2] collaborations. The fact that some of these sources do not show a very sharp flux suppression in their measured flux opens the question on the possibility of measuring photons at energies as high as above 10^{16} eV.

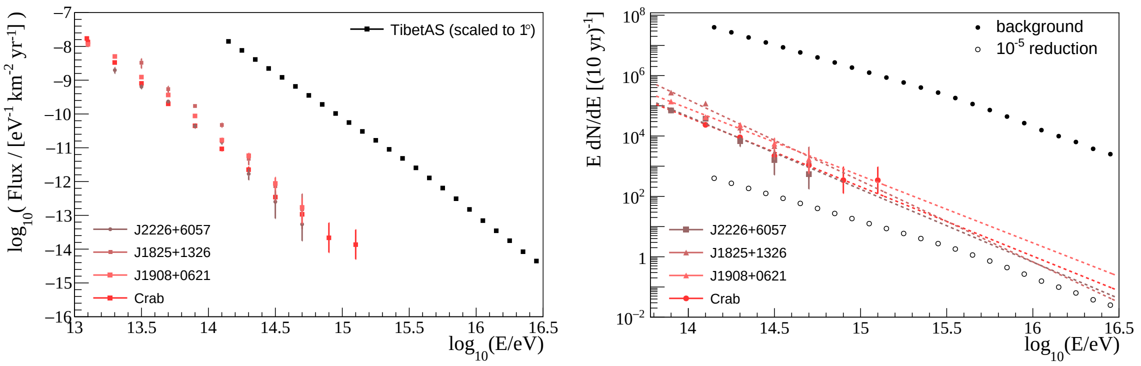
At these energies, photons interact with the background radiation fields, making the arrival horizon limited to a few tens of kpc, with just 10% of the photon flux produced at the edge of our Galaxy being able to reach us. [3]. The limitation to the gamma-ray interaction length has the advantage that the sources of these photons are surely of galactic origin, or outside the galactic plane a measure of their diffuse flux will probe the local galactic halo. Besides that, as in other energy ranges, they can probe fundamental physics like the dark matter annihilation.

We investigate the possibility of measuring the tail of the flux emitted by sources from the Southern Hemisphere. We focus on an energy range currently unexplored by any experiments in operation, from 10^{15} eV up to $10^{16.7}$ eV. The upper bound of the energy range is given by the measurements from the Pierre Auger Observatory [4] while the lower one is given by the overlap with LHAASO experiment. The planned experiments SWGO [5] and CTA [6] are not focusing on this energy interval. The ALPACA experiment [7] is progressing in its deployment and might reach this energy range if the larger array is deployed. The Northern Hemisphere Tibet AS-MD proposal exists [8] which, by enhancing the existing array, might be able to obtain the required sensitivity in this energy range. We start with estimations of the expected flux, then we describe the proposal for a Southern Hemisphere experiment, the Project for Extreme PeVatrons Searches (PEPS), in the assumption that similar source might exist in the Southern sky. Finally, we show the first preliminary studies of the expected sensitivities.

2. Expected fluxes and required separation power

The fluxes of four of the gamma-ray sources as measured by LHAASO [9, 10] are illustrated in fig. 1(a). The fluxes have been measured in a circle of 1° diameter around the sources. The measured fluxes extend above 10^{15} eV and they do not exhibit a sharp flux suppression. The energy dependency of a few other TeV sources has been measured, for example by HAWC, however, they will be included just in further studies.

We investigate the possibility of building an array of $2\,\mathrm{km}^2$ in the Southern Hemisphere. With such a detector, twice the size of LHAASO, we would be able to see events above 10^{15} eV from sources like the Crab nebula. The differential number of events that would be measured by PEPS in 10 yr is illustrated in fig. 1(b). In the same figs. 1(a) and 1(b) the flux of cosmic rays is shown with black markers. For simplicity, just the Tibet-AS data are shown [11]. The flux was scaled to the same solid angle of 1° as the measured gamma-ray flux. The background flux is a factor ten thousand higher that the gamma-ray one, thus a separation power of about 10^{-5} is required to unambiguously observe these sources. To estimate the expected number of photons and cosmic-ray contamination, the data are fitted to a simple power-law function above 10^{13} eV. In the hypothesis of a $2\,\mathrm{km}^2$ experiment with an operational time of 10 yr, between 30 and 100 photons above 10^{15} eV would be expected, with an expectation of the irreducible background below 4 events for a 10^{-5} background rejection factor. Above $10^{15.5}$ eV, these numbers become 1 to 10 photons with



(a) Measured photon and cosmic-ray fluxes.

(b) Expected differential number of events.

Figure 1: (a) The measured photon flux in a 1 ° diameter around galactic sources by the LHAASO experiment compared with the cosmic-ray flux scaled for the same sky region of 1 ° as measured by Tibet-AS. (b) The expected differential number of events in ten years for the sources measured by LHAASO compared with the background. The remaining background in the optimistic case of a 10^{-5} background suppression is illustrated with open symbols.

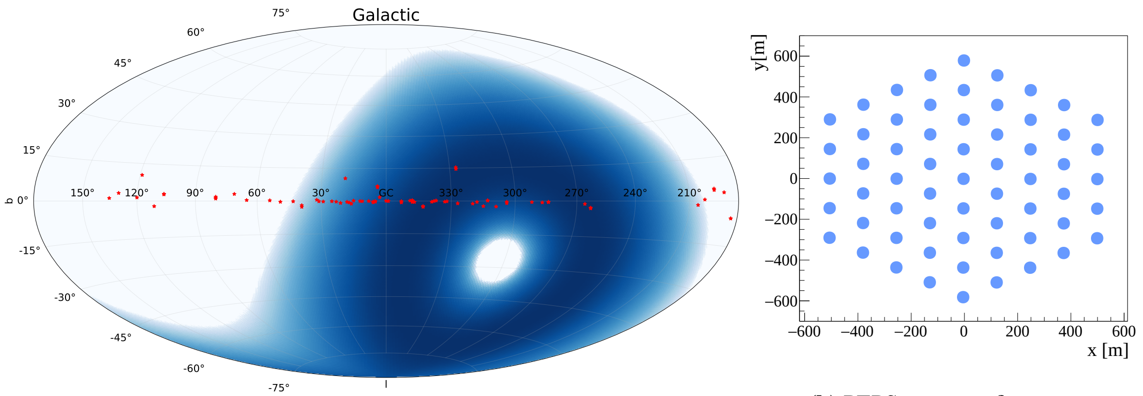
a background of 0.5 cosmic rays while above 10^{16} eV we expect less than one photon in 10 years. These numbers can be seen as upper limits, a sharp flux cut-off might further reduce these factors.

3. The Project for Extreme PeVatrons Searches (PEPS)

The High-Energy Astroparticles Project consists of an array of detectors placed in the Southern Hemisphere. To be able to take advantage of the already existing infrastructure and detectors, the site of the Pierre Auger Observatory [12] is investigated in this work [1]. The Observatory is located in the province of Mendoza, Argentina, at a latitude of -35.24 ° and 1400 m altitude. The expected field of view is shown in fig. 2(a) for air showers with zenith angles below 45 °. This location provides an excellent acceptance towards the Galactic Center. The sources that emit in the TeV range are shown with red markers and comprise the data from several gamma-ray observatories taken from the TeVcat [13]. Seeing a large fraction of the galactic plane and its center, PEPS might lead to the discovery of extreme PeVatron sources.

PEPS consists of investigating a dense array on a triangular grid, with a spacing of 145 m between the detectors (dense for ultra-high energy cosmic rays, rather sparse gamma rays). To cover ≈2 km^2 125 stations are needed. In this preliminary study we simulated just half the area, with 61 detectors (as illustrated in fig. 2(b)). The advantage of placing PEPS at the Pierre Auger Observatory is that in the region where the 433 m array is located, there are underground muon detectors buried at a depth of 2.3 m on a planned surface of 1.95 km^2 with 0.95 km^2 already covered. The measurement of the high-energy muon component can thus be employed to enhance the photon detection efficiency. The current work does not include this extra component and it focuses on water-Cherenkov detectors (WCD) placed on the ground.

[1]No formal demands to the Auger collaboration were yet made, and no commitments from the collaboration were promised.



(a) PEPS sky exposure.

(b) PEPS array configuration

Figure 2: (a) Sky coverage of PEPS assuming meaurement of air showers between 0° and 45 °. The TeV sources with known distances to the Earth of up to 20 kpc are illustrated with red markers [13]. (b) A possible configuration of PEPS on a triangular grid with a separation of 145 m between detectors.

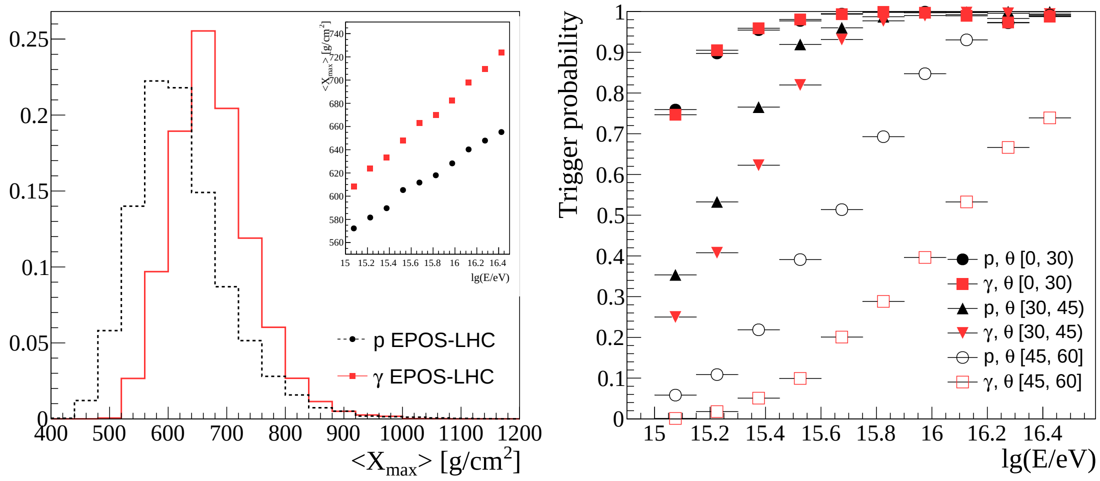
3.1 The layered Cherenkov detector concept

One of the most important characteristics that distinguish air showers initiated by photons from the hadronic-initiated ones is the small number of muons that reach the ground. A promising cost-effective detector is the layered Cherenkov detector (LCD) similar to the one proposed and characterized in [14]. The concept of the LCD[2] was developed during the R&D phase of the Pierre Auger upgrade, AugerPrime. It consists of dividing the water-Cherenkov detector (1.2 m in height and 3 m in diameter) in two optical volumes. The separation was done at 40 cm from the top, based on the fact that the electromagnetic attenuation in water is about 35 cm.

The simulations and the data from the five prototypes built showed excellent resolution for the determination of the muonic component on the ground. We simulated the same geometry as for AugerPrime, that including 3 PMTs in the top layer and one PMT in the bottom one. Based on the different contributions of the electromagnetic and muonic components to the top and to the bottom signals, the electromagnetic and muonic signals can be extracted via a simple set of linear equations, as described in section 3.3. The shape of the Auger station is somehow magical, as it makes the transformation coefficients almost universal with energy and zenith angles for a wide region of distances to the shower axis. The LCD provided a resolution of better than 15% for the determination of the muonic component in each station.

The simulations are performed with Geant4 [15] and are based on the implementation in the Offline software [16] of the Pierre Auger collaboration. The calibration of the detectors is performed using the particles produced in the atmosphere. This is taken into account in the simulations to transform the FADC counts in units of vertical equivalent muons (VEM) similar to the calibration of Auger surface detectors [17].

[2]called at that time LSD, layered surface detector



(a) Distributions of $X_{\max}$. **(b)** Trigger efficiency as a function of energy.

Figure 3: $X_{\max}$ distribution and trigger efficiencies for proton and photon-initiated air showers.

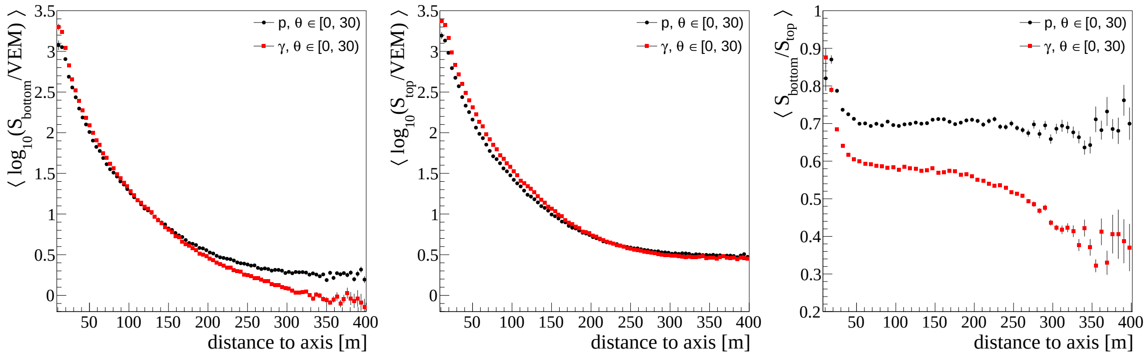
3.2 Trigger efficiencies

The altitude of the Pierre Auger Observatory is ≈1400 m which corresponds to a vertical atmospheric depth of 875 g/cm^2. Given that the maximum of the air-shower development for photons at $\log_{10}(E/\mathrm{eV}) \in [15, 16.5]$ is between 600 g/cm^2 and 720 g/cm^2 while for protons between 570 g/cm^2 and 640 g/cm^2 (see fig. 3(a)), the number of particles that reach the ground is much smaller than in the case of experiments operating at higher altitudes, closer to the maximum of the air-shower development. Studies of another location is out of scope of this study, however the possibility to go to higher altitudes will be checked. In a first step, the probability of measuring these photon and proton-initiated showers is studied in the following.

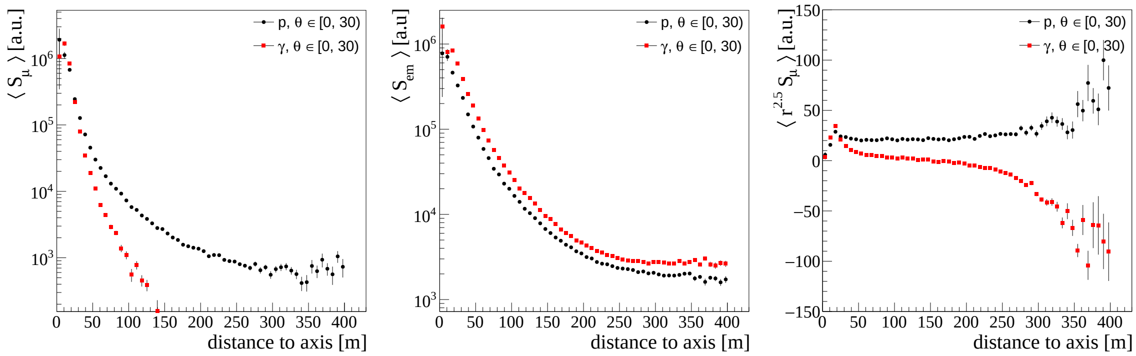
To obtain the trigger efficiency, we are using air-shower simulations produced with Corsika 7.6400 [18] using EPOS-LHC [19] and Fluka2011.2x [20]. The simulated energies are between 10^{15} eV and $10^{16.5}$ eV, while the zenith angles are lower than 65 °. The impact point on the ground has been randomized to cover the full area of the detector. We performed about 100,000 simulations for photon primaries and a similar number for proton primaries.

We defined a simplified station-level trigger based on the average signal of the PMTs from the top layer. Since the electromagnetic signal is produced mainly in the upper part of the tank, this trigger optimizes the sensitivity to electromagnetic-dominated showers. The event trigger was defined as a 3-fold coincidence of stations with the top signal larger than 2.5 VEM.

The trigger probability as a function of the energy for different zenith angle intervals is illustrated in fig. 3(b). For vertical showers with the zenith angle smaller than 30 °, the trigger efficiency is better than 70% above 10^{15} eV, while for showers up to 45 ° degrees, the array becomes fully efficient above an energy of $10^{15.5}$ eV. The trigger probabilities drop below 50% for more inclined air-showers. Based on these results we will focus the next studies on a zenith angle range up to 30 °. Further studies will include the region between 30 and 45 °.



(a) LDF in the top layer. **(b)** LDF in the bottom layer. **(c)** Ratio between top and bottom.



(d) Muonic LDF **(e)** Electromagnetic LDF **(f)** Weighted muonic signal.

Figure 4: (a,b) Example of lateral distribution functions (LDFs) for zenith angles smaller than 30° and $\log_{10}(E/\mathrm{eV}) \in [15.5, 16.0]$. (c) The average ratio between the signals from the bottom and top layers as a function of the distance to the shower axis. (d, e, f) The average muonic and electromagnetic LDFs, obtained by applying the matrix inversion and their ratio.

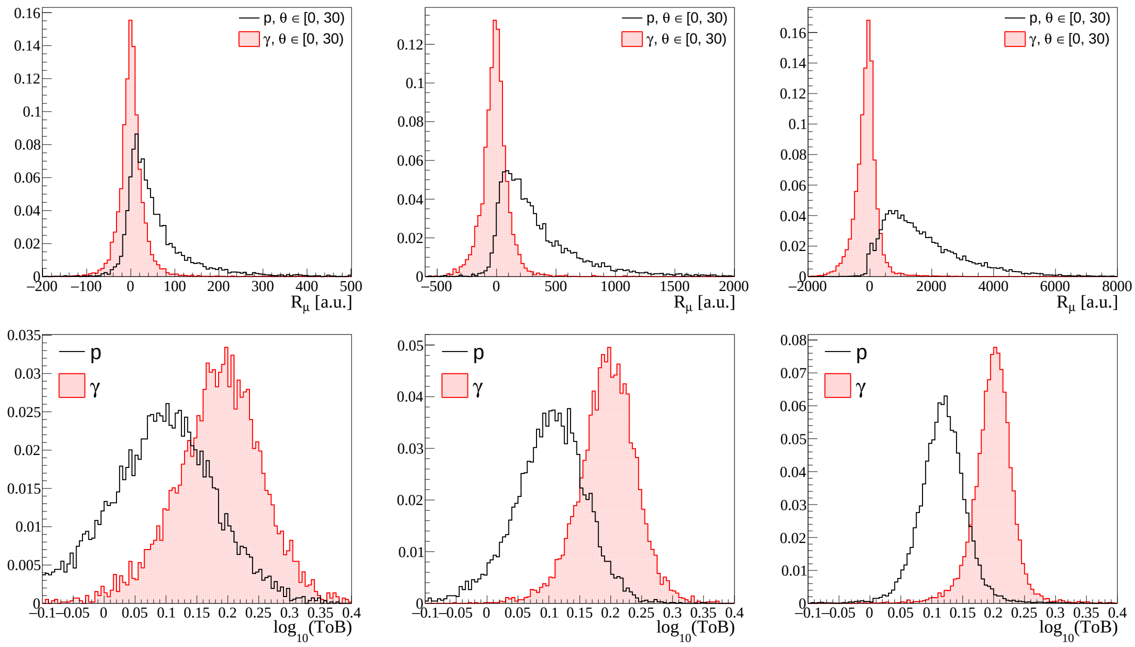
3.3 Separation between photon and proton primaries

The signals in top S_{top} and bottom S_{bottom} are a combination of the electromagnetic S_{em} and muonic S_μ signals:

$$\begin{pmatrix} S_{\mathrm{top}} \\ S_{\mathrm{bottom}} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\mathrm{EM}} \\ S_\mu \end{pmatrix}, \tag{1}$$

where a and b are about 0.6 and 0.4, respectively. The main difference between the photon and proton-initiated air-showers is carried in the muonic component. For protons, the particle distributions are dominated by muons, while for photons the muonic component is very low. The difference is already seen in the mean lateral distribution functions from the two layers shown in figs. 4(a) and 4(b), proton-initiated air showers would produce a larger signal in the bottom layer in comparison with photon-induced showers, as expected.

By solving eq. (1) one can obtain the muonic and electromagnetic signals in each station. The average LDFs for these components are shown in figs. 4(d) and 4(e). They exhibit the expected behavior of a sharp drop of the muonic component for photon primaries while the electromagnetic ones have an universal behavior. The separation between photons and protons is done based on two variables: The average ratio between the top and bottom signals from stations at more than 40 m



(a) $\log_{10}(E/\mathrm{eV}) \in [15 - 15.5]$ **(b)** $\log_{10}(E/\mathrm{eV}) \in [15.5 - 16]$ **(c)** $\log_{10}(E/\mathrm{eV}) \in [16 - 16.5]$

Figure 5: Distributions of the two separation variables for photons and protons at different energies.

from the shower axis and less than 250 m, $\log_{10}(\mathrm{ToB})$, and a weighted muonic signal that takes into account the steepness of the distributions, R_μ:

$$\log_{10}(\mathrm{ToB}) = \log_{10}\left(\frac{1}{N}\sum_{i}^{N}\frac{S_{\mathrm{top}}}{S_{\mathrm{bottom}}}\right); \quad R_\mu = \sum_{i}^{N} S_\mu \cdot r^{2.5} \tag{2}$$

The distribution of these two variables are shown in figs. 5(a) to 5(c) for three energy intervals. The variables have not been optimized, neither were they corrected for zenith angle and energy dependencies. Even with these raw and simplified quantities and with no special quality selection on the signals we were able to reach a combined separation power of better than 10^{-4} for energies larger than 10^{16} eV.

The separation power decreases while going down to 10^{15} eV becoming less than 5×10^{-3} for a 50% signal efficiency. To reach the required sensitivity at these low energies several improvements can be made and more advanced methods that include the full information from the air showers can be developed. For example a neural network architecture, which has been proven that it can reconstruct the muonic signals from water-Cherenkov detectors with very good resolution [21], can be developed. It would take into account the time distribution of the arrivals of particles on the ground, the asymmetries of the signals in the shower plane, the risetime of the signals, with a specific characteristics that in case of PEPS resolutions should be improved by the usage of the two layers carrying different information.

4. Conclusions and outlook

Preliminary studies for the Project for Extreme PeVatrons Sources (PEPS) show that the trigger efficiency for photon-induced air showers is better than 70% at 10^{15} eV even at the low altitude of the

Pierre Auger Observatory. A possible array of 2 km built with layered water-Cherenkov detectors might provide the required sensitivity at energies larger than 3×10^{15} eV, however, it is difficult to achieve it at lower energies in the investigated configuration and without advanced analysis methods. PEPS will be complementary to the existing efforts, like the SWGO [5], which aim to measure gamma-ray sources at lower energies, while a straight-forward cooperation with SWGO on detectors design and testing can be envisaged. Similar efforts on detector design will be done for the Global Cosmic Rays Observatory (GCOS) [22]. Besides the presented photon searches, PEPS can be also utilized as a prototype array for the next-generation detectors of ultra-high energy cosmic rays,by aiming PEPS also at the determination of the properties of the charged astroparticles in the transition region between the galactic to the extra-galactic origin. Two double-layered detectors are still functioning at the Pierre Auger Observatory. They can be used for understanding the trigger requirements and the performances for PEPS. Moreover, in case we will build such an array at the Pierre Auger site we can take advantage of the underground muon detector to improve upon the separation power.

These studies are a first simulation-based attempt and further studies will help in understanding if a separation power of 10^{-5} can be reached by including more information, by optimizing the detector design and the placement of the stations.

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