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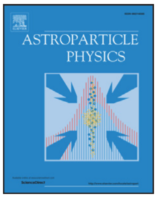

Design and expected performance of a novel hybrid detector for very-high-energy gamma-ray astrophysics

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ABSTRACT

Current detectors for Very-High-Energy γ-ray astrophysics are either pointing instruments with a small field of view (Cherenkov telescopes), or large field-of-view instruments with relatively large energy thresholds (extensive air shower detectors).

In this article, we propose a new hybrid extensive air shower detector sensitive in an energy region starting from about 100 GeV. The detector combines a small water-Cherenkov detector, able to provide a calorimetric measurement of shower particles at ground, with resistive plate chambers which contribute significantly to the accurate shower geometry reconstruction.

A full simulation of this detector concept shows that it is able to reach better sensitivity than any previous gamma-ray wide field-of-view experiment in the sub-TeV energy region. It is expected to detect with a 5σ significance a source fainter than the Crab Nebula in one year at 100 GeV and, above 1 TeV a source as faint as 10% of it.

As such, this instrument is suited to detect transient phenomena making it a very powerful tool to trigger observations of variable sources and to detect transients coupled to gravitational waves and gamma-ray bursts.

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1. Introduction

High energy gamma rays are important probes of extreme, non thermal, events taking place in the universe. Being neutral, they can cover large distances without being deflected by galactic and extragalactic magnetic fields. This feature enables the direct study of their emission sources. The gamma emission is also connected to the acceleration of charged cosmic rays and to the production of cosmic neutrinos. Gamma-rays can also signal the existence of new physics at the fundamental scales, namely by the annihilation or decay of new types of particles, as it is the case for dark matter particles in many models. This motivation, associated to the advances of technology, has promoted a vigorous program of study of high energy gamma rays, with important scientific results (see [1–4] for a summary of the main achievements).

The detected sources of cosmic gamma-rays above 30 MeV are concentrated around the disk of the Milky Way; in addition there is a set of extragalactic emitters. About 3000 sources emitting above 30 MeV were discovered, mostly by the Large Area Telescope (LAT) detector [5] onboard the *Fermi* satellite, and some 200 of them emit as well above 30 GeV [6] (see Fig. 1) – the region which is labeled the Very High Energy (VHE) region.

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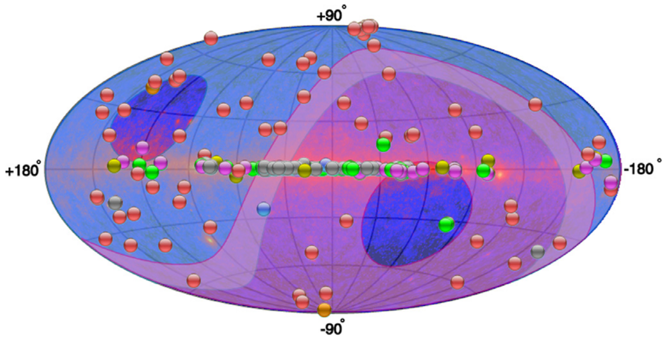

Fig. 1. Sources of VHE emission displayed in galactic coordinates. The background represents the high-energy gamma-rays detected by *Fermi*-LAT. The clear blue (dominant on the left side) area corresponds to the visible region within 30° of the zenith from a detector at a latitude of 22° in the Northern hemisphere while the pink (dominant on the right side) shows the corresponding region in the Southern hemisphere.From http://tevcat.uchicago.edu/, June 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Our Galaxy hosts about half of the VHE gamma-ray emitters [7] and most of them are associated to supernova remnants of various classes (shell supernova remnants, pulsar-wind nebulae, etc.). The remaining emitters are extragalactic. The angular resolution of current detectors, which is slightly better than 0.1°, does not allow to assign the identified extragalactic emitters to any particular region in the host galaxies; however, there is some consensus that the signals detected from the Earth must originate in the proximity of supermassive black holes at the center of the galaxies [8].

Still, many problems remain open, of which we may mention:

- *The origin of cosmic rays* – supernova remnants (SNRs) are thought to be the sites for the acceleration of protons up to few PeV. However, the mechanism of acceleration of particles to energies of that order is still to be established experimentally. The study of the photon yield from Galactic sources for energies larger than 100 GeV and all the way up to PeV, might solve the problem (see for example [9]). Actually, photons, which come from π^0 decay, correspond to hadronic cascades initiated at energies at least an order of magnitude larger.
- *The propagation of gamma-rays* – tells us about their interaction with the cosmic background radiation and is a probe to cosmology themes.
- *New physics* – the ultimate nature of matter and of physics beyond the Standard Model, dark matter or new particles in general, the energy density of the vacuum or even quantum gravity may leave imprints in the spectrum of VHE gamma rays. High-energy gamma-ray astrophysics is sensitive to energy scales important for particle physics. For instance, cold dark matter is expected to be found in the 100 GeV scale; supersymmetric particles could appear at the TeV scale; and the Planck scale (an energy $\sim 10^{19}$ GeV, corresponding to a mass $\sqrt{\hbar c/G}$) could be probed indirectly (for discussion see for example [1]).
- *Transients* – Many VHE sources are characterised by variability, and it is important to be able to detect and measure the corresponding flares. Such flares have a duration that can go from few seconds – like for the short gamma-ray bursts or the expected counterparts of gravitational waves – to minutes for the long gamma-ray bursts, to minutes, hours or even days for the accretion flares of blazars (see e.g. [10] and references therein).

The layout of this paper is the following. In the Introduction we have briefly presented the field of very-high-energy gamma-ray astrophysics. In Section 2 we outline the characteristics of the existing detectors, and we explain why a large field-of view detector is needed. In Section 3 we make a case study with a possible design for such a detector. In Section 4 we describe the characteristics of the gamma-ray signal and of its background, and the various Monte Carlo samples used in the analysis of the performance of the proposed detector. In Section 5 we evaluate the performance of such a new detector using the simulation. We conclude the paper with final remarks and a summary in Section 6.

2. Detection of gamma rays

The direct detection of primary X/γ-rays is only possible using satellite-based detectors since the radiation is absorbed in the atmosphere. However, the cost of space technology limits the size of satellite-borne detectors to, roughly, areas of about one square meter. The largest and most sensitive space-based gamma detector is *Fermi*, with its high-energy sub-detector, the LAT, with an area of about 3 m^2, and an effective area – the product of the geometrical area by the energy dependent detection efficiency – of about 1 m^2 for a gamma-ray with an energy of 1 GeV [11].

If the energy of a primary cosmic photon is above some tens of GeV part of the products of the air shower, initiated by the interaction of the photon with the atmosphere, can reach the Earth surface. Ground-based detectors have a large effective area, so their sensitivity is high, however they are subjected to a large amount of background events, typically charged cosmic rays. They outperform satellite-based detectors, like the *Fermi*-LAT, in the VHE energy region. The placement of such detectors at high altitude reduces the amount of atmospheric absorption, allowing to reach lower primary energies.

VHE gamma ground based detectors can be divided in two major classes: the Extensive Air Shower (EAS) arrays and the Cherenkov telescopes.

2.1. EAS Arrays

A typical EAS array consists of a large number of detectors that record the secondary shower particles that reach the ground. Although the energy resolution is poor, it has a very high duty cycle and a large field of view. Currently, the energy threshold of EAS detectors is at best in the 0.5 TeV–1 TeV range. At such energies, fluxes are low and large surfaces of the order of 10^4 m^2 are required. This can be achieved:

- either by using a sparse array of scintillator-based detectors, as for example in the Tibet-AS [12] (for an energy of 100 TeV there are about 50,000 electrons in the shower at mountain-top altitudes), which has already finished operations;
- or by a dense coverage of the ground, to ensure efficient collection and hence lower the energy threshold. The ARGO-YBJ detector [13] an array of resistive plate chambers (RPC) at the Tibet site, followed this approach.

The largest EAS detector, dedicated to (very) high-energy gamma-rays, presently in operation is the High Altitude Water Cherenkov (HAWC) array [14,15] which is in Mexico at an altitude of 4100 m.

The main problem in this class of detectors is the background rejection, since the flux of charged cosmic rays above 0.5 TeV is about a thousand times larger than that from the most intense gamma source. Muon detectors are useful instruments to reduce background. Background rejection can be otherwise based on the reconstructed shower topology, which is different for gamma-initiated atmospheric showers and for hadron-initiated showers. The direction of the primary particles is estimated from the arrival times with an angular precision which can reach about 1° at best.

There are new plans to build or expand new, larger and more sensitivity, experiments, for instance, the LHAASO detector [16],

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