Gamma-astronomy in the UHE region by using an array of muon detectors

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Abstract. **The future gamma astronomy experiments should face the gamma sources search in a wide energy range: from approximately 100 GeV up to tens of TeV. To observe a statistically significant sample of photons with energies above tens TeV, large ground-based detectors are needed. The primary gamma-rays are measured by detecting the extensive air showers (EASs) produced by their interaction with the atmosphere. In this paper the contribution of the measurement of the muon content in EAS detectors operating to search gamma sources at the energy of tens TeV is presented. By using Monte Carlo methods, a muon detector, distributed over an area of about 1 km^2, was simulated. The sensitivity of this apparatus is discussed; the minimum measurable fluence is also presented.**

***Keywords*: Muon-detector, Gamma-astronomy, UHE range**

I. INTRODUCTION

In the last few decades, the field of the gamma-ray astronomy has developed considerably, thanks to the increasing precision of instruments designed to investigate unexplored energies. So far the most competitive ground-based instruments are able to detect point-like as well as diffuse and transient sources with a sensitivity up to some percent of Crab flux in the energy region spanning up to tens of TeV. Different techniques are used, based on the measurement of Cerenkov light, of the charged particles and of the fluorescence light produced in the extensive atmospheric showers generated by the interaction of the primary gamma-rays with the atmosphere.

In this energy range two techniques [4] can be used: the Imaging Arrays of Cerenkov Telescopes (IACTs) and the Extensive Air Shower arrays (EASs). The atmospheric Cerenkov technique has emerged as a powerful tool for gamma-ray astronomy at the multi-TeV energies. With their angular and energy resolution, better than that of the EAS arrays, IACTs are unsurpassed in sensitivity to detect gamma-ray point-sources at these energies. On the other hand, IACTs have small duty cycle because they can operate only on clear moonless nights and they have small field of view ($\sim$ few msr), while EAS arrays continuously monitor the sky with a field of view of the order of 2 sr and with high duty cycle ($>$ 90 %). IACTs are excellent detectors to study source morphology and energy spectra they are not suitable to perform a sky survey, for monitoring sources for transient emission such as gamma-ray bursts (GRBs) and flaring active galactic nuclei (AGN), or for searching for extensive sources. On the contrary, EAS detectors are excellent sky monitors for transient and large low-emissivity sources.

To face out the search of gamma-ray sources at much higher energies (above the tens TeV), detecting new source classes that are below the sensitivity of current instruments, new techniques are needed.

In this paper we explore a new approach to detect gamma-ray sources in the ultra high-energy (UHE) region based on a large area EAS detector allowing the measurement of the penetrating component of EASs, consisted of energetic muons. As a matter of fact, beyond a particular energy threshold, the muon content produced by gamma-ray-induced air showers is significantly sizable and can be measured with dedicated instruments. In the UHE region the muons produced in EASs play a key role as powerful tool for discriminating between gamma-induced showers by hadron-induced showers, increasing considerably the sensitivity of ground-based EAS detectors.

Moreover, the measurement of the muon component of the EASs is also an useful handle to study the cosmic ray elemental composition: the heavier the primary particle the larger the muon content in the produced showers.

II. DETECTOR LAYOUT

UHE gamma-ray astronomy needs huge ground-based detectors which can overcome, with their large exposure area, the low gamma-ray flux as well as the small number of muons, compared with photons and charged particles, produced in the showers.

In this work the performance of a muon detector array 1 distributed over an area of about 1 km^2 is presented. The features of the array are summarized in table I. The array is designed to reach a competitive sensitivity to gamma-ray sources in a wide energy range, from 1 TeV to 10^4 TeV, by measuring muons and charged particles generated in EASs. The facility was thought as made of 148 towers. Rejection of the cosmic ray background was accomplished by placing three layers

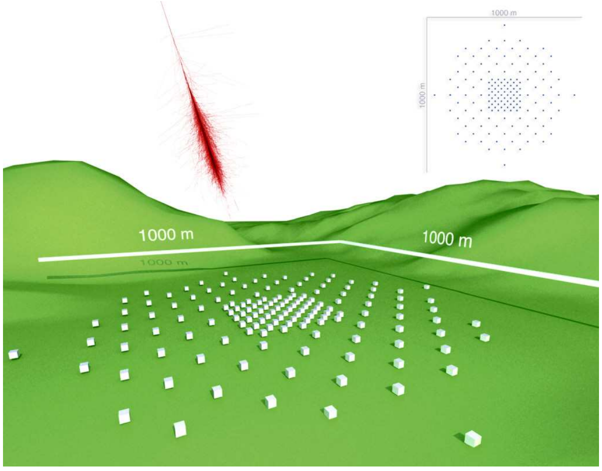

Fig. 1. Image of the detector array simulated in this work. The instrumented area is of order 1 km^2.

of tracking chambers and an absorber (like concrete) in each tower (see figure 2). The upper layer measures all charged particles coming from the shower front. The two lower layers detect the penetrating component, like muons, crossing the absorber. All the three layers track the muons generated in an EAS, contributing to better reconstruct the incoming direction of gamma-ray primaries.

In order to improve the sensitivity of the apparatus, several configurations of the array were studied. The configuration discussed in this paper, figure 1, shows an inner area with an high density of towers to enhance the sensitivity at lower energies ($\sim$TeVs), reducing the energy threshold, and an outer area with a sparse density of towers to detect gamma-induced showers at higher energies (hundreds TeV).

III. SIMULATIONS

Present analysis was performed using the shower simulation program CORSIKA 6.7.10 [1]. Simulations are based on two hadronic interaction models, GHEISHA [2] at low energies and QGSJET-II [3] at higher energies. Events were generated on six fixed values of energy in a range from 1 to 10^4 TeV, for both gamma-ray and proton primaries at zenith angle of $0°$. A total of $\sim 2{\times}10^4$ proton-induced showers and $\sim 2{\times}10^4$ gamma-induced showers were generated in order to estimate the performance of the detector.

TABLE I
FEATURES OF THE EAS ARRAY

Altitude	4000 m
Side of the array	$\lesssim 1$ km
Number of towers	148
Tower spacing:	
- inner array	$\sim$ 28 m
- outer array	$\sim$ 70 m
Tower area	10×10 m^2
Geometrical area	$\sim 1 \cdot 10^6$ m^2
Instrumented area	$1.48 \cdot 10^4$ m^2

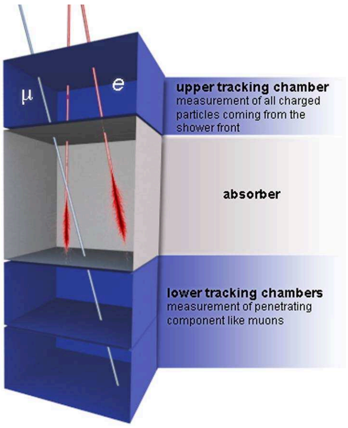

Fig. 2. Sketch of a tower of this work. The tower is made of three layers of gaseous tracking chambers and an absorber.

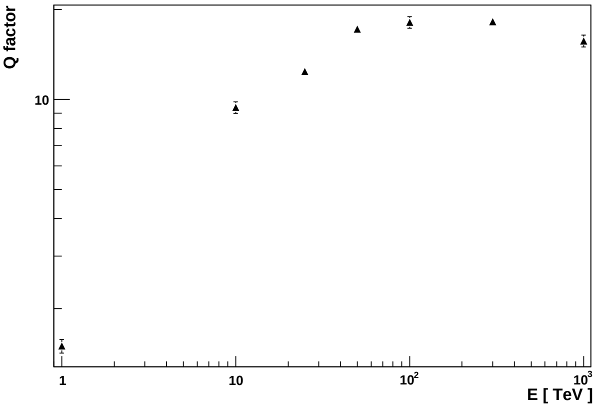

Fig. 3. The *Q-factor* obtained by means of the muon measurement .

The layout of the apparatus was simulated taking into account the integral distribution of the muon density with respect to the distance from the core of the shower. Simulated showers in the UHE region show that $\sim 75\%$ of the number of muons is contained within $\sim$ 350 m of distance from the core. In order to collect the maximum number of muons by means a reasonable number of towers, an area of 200-meter side length in the core of the array was instrumented at 15%, which means with 60 towers. Moreover, due its high density of towers this configuration allows high performance at low energies and a lower energy threshold.

Each tower consists of three layers of gaseous detectors equipped with x, y readout. The geometry of the chambers as well as the efficiency were implemented for each tower. Two general triggers were simulated, one based on a minimum number of muons detected by each tower, a second trigger is based on a minimum number of charged particles detected by all the towers. The two trigger reached a full efficiency $(\sim 90\%)$ for all the events analized. In this papaer the trigger based on a minimum number of charged particles was used. The effective area (A_{eff}) of the array was evaluated by means of the Monte Carlo data, the trigger efficiency ϵ_{TRG} was evaluated also and a row estimation of the angular resolution was estimated. The efficiency to detect gamma-induced showers (ϵ_γ) and hadron-induced showers (ϵ_h) by using the measurement of the muon content in the showers, were evaluated. In figure 3 the *Q-factor* (quality factor) to discriminate gamma-induced showers and hadron-induced showers obtained by means of the muon measurement is reported. The plot shows values of about 20 at energies greater than tens TeV.

IV. INTEGRAL FLUX SENSITIVITY

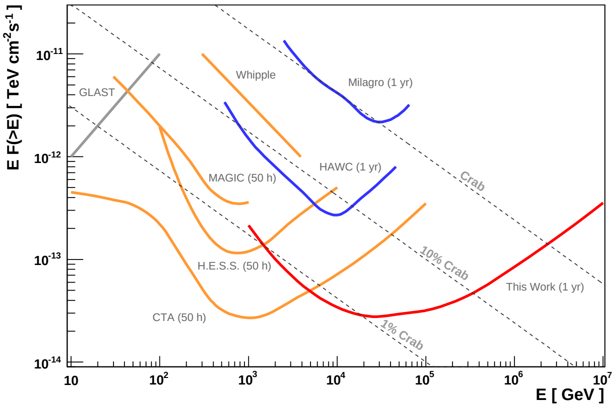

Fig. 4. The figures shows the expected sensitivity of this work (red curve) and that of imaging air Cerenkov telescopes (MAGIC, H.E.S.S., CTA [4] and Whipple), space-based detector (GLAST-FERMI [4]) and EAS arrays (Milagro, HAWC [4]).

Potentialities of the simulated apparatus are expressed in terms of the minimum measurable flux of gamma-rays, defined by the confidence level required for detection or by the statistics of the detected photons. A 5σ excess of gamma-rays above the background was considered. The flux sensitivity is estimated for one year of observations on Crab Nebula.

Crab Nebula, detected in the TeV energy range by Whipple in 1989, is the standard candle for the gamma-ray astronomy because of its large steady flux. As almost all gamma-ray sources, its differential energy spectrum can be approximated by a power law given by

$$\frac{d\phi}{dE} = 2.83 \cdot 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-2.62} \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$$

as seen from the Crab Nebula in the TeV-energy range [5]. The performance of the apparatus is reported in figure 4. The integral flux sensitivity $E \cdot F(> E)$ is reported. The picture shows clearly the capability of the apparatus, the measurement of the muon content in EASs allows the gamma-sources search at the energies greater than tens TeV.

V. CONCLUSIONS

By using the discrimination criterion based on the muonic component of the showers, the performance of a 1 *km*-area EAS array is presented. The detector is realized by means of distributed towers allowing the measurement of the charged particles of the shower front as well as the measurement of the penetrating particles (muons). The effective area (A_{eff}), the trigger efficiency ϵ_{TRG} and the the so-called *Q-factor* (quality-factor) allowing to increase the sensitivity of the apparatus for the detection of gamma-ray sources up to tens TeV, were evaluated. The results obtained were compared with those coming from others experiments (Milagro, HAWK, HESS, CTA, . . .) with reference to an important source in the gamma-ray astronomy: the Crab Nebula. From this comparison it is possible to conclude that the capability of detecting the muon component of the showers can make an EAS apparatus competitive in the UHE region. This feature in fact plays a key role in the sensitivity of the apparatus opening the search for sources in energetic regions not yet explored.

Specifically, the sensitivity of the simulated apparatus, reached thanks to the measurement of the EAS muon component in the region of the tens TeV, is of order 10^{-2} Crab, and it is of the order of 0.1 Crab at about 1000 TeV.

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