Gamma-Ray Astronomy around 100 TeV with a large Muon Detector operated at Very High Altitude

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Abstract: Measurements at 100 TeV and above are an important goal for the next generation of high energy γ-ray astronomy experiments to solve the still open problem of the origin of galactic cosmic rays. The most natural experimental solution to detect very low radiation fluxes is provided by the Extensive Air Shower (EAS) arrays. They benefit from a close to 90% duty cycle and a very large field of view ($\sim$2 sr), but the sensitivity is limited by their angular resolution and their poor cosmic ray background discrimination. Above 10 TeV the standard technique for rejecting the hadronic background consists in looking for *"muon-poor"* showers.

In this paper we discuss the capability of a large muon detector (A_μ=2500 m^2) operated with an EAS array at very high altitude (>4000 m a.s.l.) to detect γ-ray fluxes around 100 TeV. Simulation-based estimates of energy ranges and sensitivities are presented.

Introduction

The recent TeV results of the HESS experiment, suggest the existence of a population of galactic γ-ray sources with emission extending beyond 10 TeV in the 5 to 15% Crab flux range (for E > 1 TeV). These sources, associated with nearby shell-type or plerionic SNR, the most probable factories of galactic cosmic rays, can be studied by the detections of gamma-rays (and neutrinos) emission in the VHE/UHE energy domain. Therefore, a detector capable to perform a continuous all-sky survey at a level of about a percent of the Crab flux up to 100 TeV is needed. The search and study of *"Cosmic PeVatrons"* and the surrounding regions is one of the main scientific issues to be addressed by the next generation of ground-based γ-ray astronomy detectors [1].

The only ground-based technique allowing simultaneous and continuous coverage of a significant fraction of the sky (about all that overhead) consists in the sampling of shower particles with the EAS arrays. Their large field of view and the high duty cycle (>90 %) suits them to perform a γ-ray sources population survey at VHE/UHE energies. But more important is their unique potential that allows to have an effective monitoring of γ-ray activity of a large number of highly variable sources like blazars and microquasars, as well as the possibility for independent detection and study of solitary GeV-TeV γ-ray events like classical GRBs [1]. In addition, the recent observations of unidentified extended sources from the Galactic plane [2] and in the Cygnus region [3] reported by the Milagro Collaboration demonstrate the strength of EAS arrays in finding diffuse and extended sources. The discovery science could be, therefore, a feature of EAS-arrays.

The limited sensitivity in detecting γ-ray point sources, characteristic of EAS experiments, is mainly due their poor gamma/hadron separation power, limited angular resolution and high energy threshold. The exploitation of a full coverage approach at very high altitude leads to the improvement of angular resolution of about 0.2° and to the reduction of the energy threshold well below the TeV region. The standard technique to perform an gamma/hadron discrimination above 10 TeV by EAS arrays consists in looking for *"muon-poor"* showers.

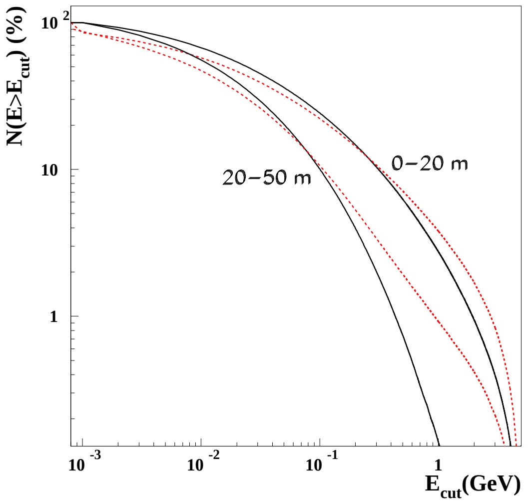

Figure 1: Integral energy spectra of electromagnetic particles ($e^{\pm}$, γ) produced at 4300 m asl by proton- (dotted red lines) and γ-induced (full black lines) showers in two different distances from the core.

In this paper we discuss the capability of a large muon detector (A_{μ}=2500 m^2) operated with an EAS array at very high altitude (>4000 m a.s.l.) to detect γ-ray fluxes around 100 TeV. An estimation based on the simulation of energy range and sensitivities is reported.

γ-hadron separation

We have simulated, via the Corsika/QGSJet code [4], proton- and γ-induced events with energy spectra [5, 6] ranging from 0.1 TeV to 1 PeV at an observational level of 4300 m asl (606 g/cm^2), corresponding to the YangBaJing Cosmic Ray Laboratory. There are located two EAS arrays: the conventional Tibet ASγ experiment and the full coverage detector ARGO-YBJ. From the study of shower phenomenology it results:

(1) The muon content of proton-induced showers exceeds, as expected, the muon content of γ-showers by about two orders of magnitude.

(2) The muon component in γ-induced events has a flatter lateral distribution for core distances smaller than a few tens of meters.

(3) The number of low energy e.m. particles ($e^{\pm}$, γ) in γ-showers exceeds the corresponding number in proton showers (see Fig. 1).

(4) Inside the core region (R<20 m), for particle energies above about 400 MeV, the number of $e^{\pm}$ and γ in proton showers is higher than the corresponding numbers in γ-showers.

(5) Outside the core region (for R>20 m) the number of e.m. particles in proton showers starts exceeding the corresponding numbers in γ-showers at lower energies (about 100 MeV). For E>1 GeV the two components differ by more than 1 order of magnitude: high energy e.m. particles outside the core strongly indicate proton-induced showers. This number is comparable to the number of muons.

In addition, the high energy tail of secondary e.m. particles in proton-induced showers is responsible for non-uniformity in the spatial distribution of shower particles. Consequently, an appropriate muon detector operated outside the shower core region (R>30 m), evaluating all available high energy (E> 300 MeV) secondary components of air showers (μ, $e^{\pm}$, γ), allows a γ/hadron discrimination which considerably goes beyond ordinary muon counting [7]. The layout for the muon detector investigated in this preliminary study consists of 4 detectors each 24×26 m^2 large (2500 m^2 total area) simmetrically distributed on the boundary of a 150×150 m^2 large EAS array (for example, out of the four sides of the main building of the ARGO-YBJ experiment [8]). The envisaged detector is constituted by 5 tracking planes made with streamer tubes shielded by $\sim$1 m of concrete in order to absorb particles with energy lower than $\approx$400 MeV. Therefore, in the following we will refer to ”muons” as to all the high energy particles.

In comparison with hadronic showers, the muon content distribution of γ-induced events is significantly shifted toward lower values of N_{μ} and includes a much larger fraction of events with no

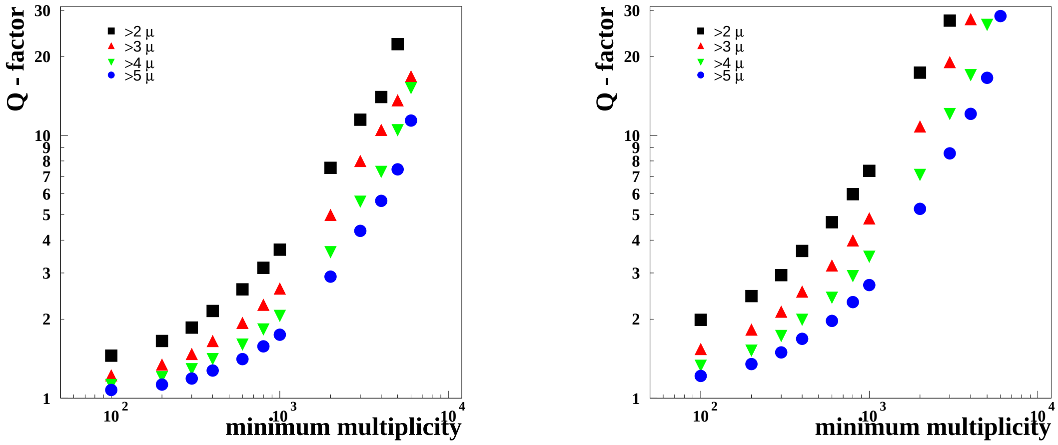

Figure 2: Q-factor vs. minimum multiplicity for different cuts (2, 3, 4, 5 μ). In the left plot all μ-detectors have been used, in the right one only μ-detectors outside the shower core region (R$>$ 30 m) have been taken into account.

muons detected. Therefore, we define as *muon-poor* those events that have a value of N_μ less than a value chosen to optimize the sensitivity to γ-ray sources. In order to evaluate the improvement is sensitivity due to the presence of a muon detector, we calculate the so-called *"Q-factor value"* $Q_f = \epsilon_\gamma(r_p)/\sqrt{1-r_p}$, where r_p is the fraction of cosmic ray background rejected with a given N_μ cut and $\epsilon_\gamma(r_p)$ is the fraction of γ-induced showers which survives to this cut.

Two different analysis procedures have been performed: (1) all muon detectors have been used in the calculation of the muon content; (2) only μ-detectors 30 m farther from the reconstructed shower core position have been taken into account. In Fig.2 the Q-factor values as a function of multiplicity for different N_μ cuts are shown. The multiplicity is the number of charged particles N_{ch} sampled by a 100$\times$100 m^2 full coverage detector whose 4 sides are surrounded by the 4 μ-detectors. In the left plot all μ-detectors have been used, in the right one only μ-detectors outside the shower core region (R$>$ 30 m) have been taken into account to calculate the muon content. As expected, the Q-factor improves operating far from the core.

Sensitivity to γ-ray sources

In order to evaluate the Minimum Detectable Flux (MDF) improvement due to the calculated Q-factors we considered as a reference sensitivity the ARGO-YBJ MDF calculated for internal events, at 5 standard deviation in one year of observation for a Crab-like source [8] (red curve of Fig. 3). The results of these calculations with procedure (2) are shown in Fig.3 by the blue curve. For a conservative estimation of the MDF we exclude cuts at very low (0, 1 and 2) muon content, where there is a potential background from mismatched events, and we consider that only the showers with $<$3 muons on the detectors are due to a γ-ray signal. At 30 (80) TeV the improvement in the MDF, due to the rejection of showers with $\geq$ 3 detected muons, is a factor 25 (100), because at sufficiently high energy the gamma measurement is background-free.

The rejection power for diffuse γ-rays

The detection of an isotropic diffuse flux of UHE photons depends not only on the size and the sophistication of the detectors but also on the properties of the γ-ray showers. In fact, if these events have the same muon content as hadronic showers the detection of any diffuse γ-ray fluxes would be impossible. In order to evaluate the rejection

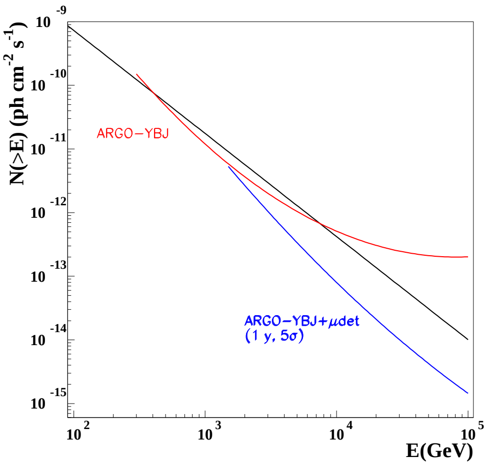

Figure 3: Minimum Detectable Flux (1 year, 5σ) compared with the Crab spectrum (black line). The red curve shows the ARGO-YBJ sensitivity, the blue one the MDF due to a 2500 m^2 μ-detector.

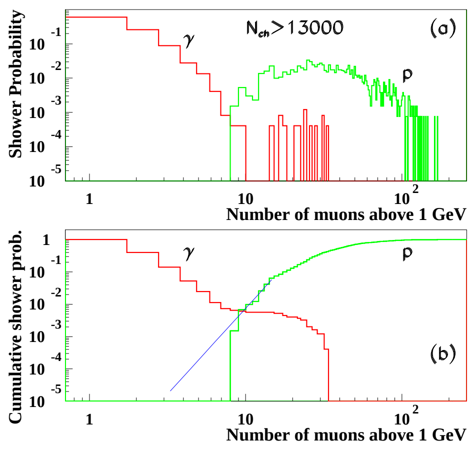

Figure 4: (a) Probability that a photon or proton shower generates a given number of muons. (b) Inclusive probability for the histogram shown in (a).

power for proton-induced showers we have studied how frequently hadronic showers fluctuate in such a way to have a low muon content indistinguishable from γ-induced events. In Fig.4 we show the probability that a photon or proton shower generates a given number of muons on the simulated detector, assuming for both primaries the same spectral index -2.7. We note that the fluctuations about the mean values do not follow the Poisson statistics. The inclusive probability distributions are reported in the lower panel of the figure. For proton (photon) showers the histograms bars in the inclusive distributions represent the probability that a shower contains less (more) muons than the upper (lower) limit of the bin. The plot refers to showers with N_{ch} $\geq$13000 (photon median energy $\sim$150 TeV). We have conservatively fitted the proton distribution overestimating the background in order to predict their level at very low muon content [9]. In Table 1 are listed the implications for γ-ray detection for showers with N_{ch} $\geq$13000. In this energy region a significant fraction of the cosmic rays could be heavy nuclei, yielding larger muon numbers compared to proton showers alone. Therefore, we are studying here a worst-case scenario, as protons are most likely to fake γ-rays. From MC calculations we conclude that diffuse γ-rays of $\sim$ 150 TeV energy can be observed to a level $\sim$$10^{-5}$ of the cosmic ray background if the systematic uncertainties of the detector are understood at the same level.

N_μ	<3	<4	<5
Fraction of γ-ray retained	85%	94%	97%
Background level	10^{-5}	$6{\cdot}10^{-5}$	$2{\cdot}10^{-4}$

Table 1:

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