Gamma-ray astronomy with a large muon detector in the ARGO-YBJ experiment

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Abstract. The ARGO-YBJ experiment, currently under construction at the YangBaJing Laboratory (Tibet, P.R. China, 4300 m a.s.l.), could be upgraded with a large ($\sim$ 2500 m^2) muon detector both to extend the sensitivity to γ-ray sources to energies greater than $\sim$ 20 TeV and to perform a cosmic ray primary composition study. In this paper we present an evaluation of the rejection power for proton-induced showers achievable with the upgraded ARGO-YBJ detector. Minimum detectable γ-ray fluxes are calculated for different experimental setups.

INTRODUCTION

The main problem in ground-based γ-ray astronomy is the rejection of the cosmic ray isotropic background. Only the Imaging Atmospheric Cherenkov Telescope (IACT) technique has brilliantly solved this problem achieving remarkable sensitivities to γ-ray sources. Since the first observation of the Crab Nebula reported in 1989 by the Whipple Collaboration, Cherenkov telescopes improved very much. Nevertheless, due to the intrinsic limitations of the Cherenkov technique (narrow field of view and reduced duty cycle), up to now only a small number of VHE γ-ray sources has been detected. In fact, the all sky survey is unfeasible with IACTs because these detectors require pointing at known or candidate sources due to their small field of view.

A γ-ray sources population survey is the chance of the Extensive Air Shower (EAS) arrays since they are large field of view instruments ($\sim$ 2 sr) with high duty cycle ($>$ 90%). The discovery science is therefore a feature of EAS-arrays.

The characteristic limited sensitivity of EAS experiments can be increased lowering the energy threshold (by operating at very high altitude) and improving the angular resolution (by reducing the space-time pixels dimensions of the apparatus with a *"full coverage"* approach).

Since showers induced by the isotropic flux of cosmic rays are very similar to photon-induced events, techniques for rejecting this hadronic background are fundamental. The standard technique is to look for *"muon-poor"* showers. In fact, the muons are generated from the decay of charged pions and kaons, which, in hadronic showers, are produced in nucleus-nucleus interactions, while in photon showers come out only in the photoproduction processes. The ratio between the cross sections of photoproduction and nucleus-nucleus interaction processes is $\approx 10^{-3}$, resulting in $< N_\mu^\gamma > / < N_\mu^h > \approx 3 \cdot 10^{-2}$. The main limitations of this technique is due to the large fluctuations in hadron-initiated showers and to the small number of muons. In order to evaluate the power of

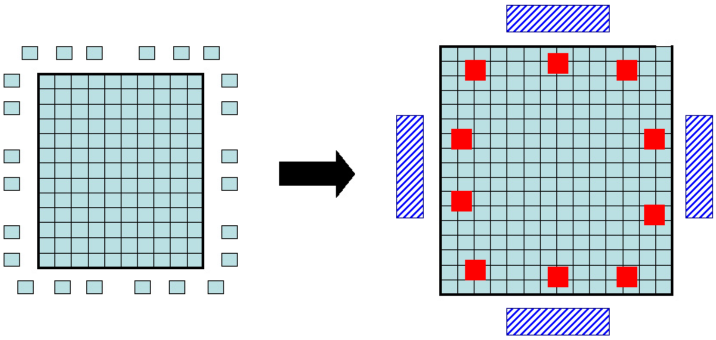

FIGURE 1. The ARGO-YBJ experiment layout. Each rectangle is a Cluster, a set of 12 contiguous RPCs. In the left side the apparatus under construction is shown, in the right side the envisaged upgrades are sketched (see text).

this background rejection technique it is important to know how frequently hadronic showers fluctuate in such a way to have a low muon content as the one resulting from γ-induced events.

In this paper we present a comparison of different ARGO-YBJ sensitivities to γ-ray sources calculated for the detector under construction and for an extended version of the apparatus. Two different layouts of the muon detector have been envisaged and their contribution to increase the sensitivity has been estimated. Finally, an evaluation of the power of the μ-poor showers technique for rejecting hadronic background in the diffuse γ-ray search is given.

THE ARGO-YBJ EXPERIMENT

The ARGO-YBJ experiment, currently under construction at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l.), will be operating over the next years with the aim of studying cosmic rays, mainly cosmic γ-radiation, at an energy threshold of a few hundreds of GeV, by detecting small size air showers. The ARGO-YBJ apparatus will consist of a full coverage array of dimension $\sim 74 \times 78$ m^2 realized with a single layer of Resistive Plate Counters (RPCs), 280×125 cm^2 each. The area surrounding the central detector core, up to $\sim 110 \times 100$ m^2, will be partially ($\sim$ 50%) instrumented with RPCs. A lead converter 0.5 cm thick will uniformly cover the detector plane. The schematic layout of the apparatus is shown in Fig.1 (left side). For a more detailed description of the experiment see [1].

The main features of the ARGO-YBJ experiment are: (1) time resolution $\sim$ 1 ns; (2) space information from strips 6.7×62 cm^2 large; (3) time information from pads 56×62 cm^2 large. Due to the high pixel density the detector will be able to image the shower profile with an unprecedented granularity.

In order to extend the sensitivity to γ-ray sources at higher energies two upgrades to the ARGO-YBJ experiment have been envisaged (see Fig.1, right side):

1. the extension of the central carpet to include the guard-ring for a total of 14×17 Clusters.

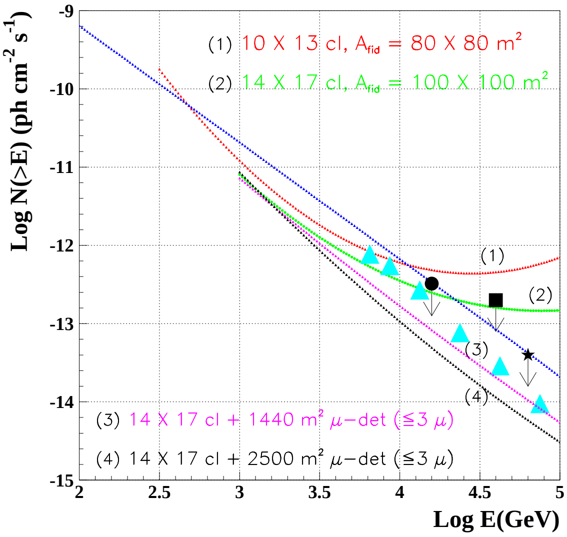

FIGURE 2. Comparison of different ARGO-YBJ sensitivities. The straight line shows the spectrum measured by Whipple [6] extrapolated up to 100 TeV. The 90% upper flux limits from other experiments are also plotted (circle: HEGRA [2], square: Cygnus [3], star: CASA-MIA [4]). The triangles represent recent data from HEGRA [5].

2. the installation of a large area muon detector with tracking capability.

In this paper two different layouts for the muon detector have been considered:

- a 1440 m^2 total area consisting of 10 detectors each 12×12 m^2 large, simmetrically distributed on the boundary of the enlarged carpet (the red squares in the right side of Fig.1);
- a 2500 m^2 total area consisting of 4 detectors each 24×26 m^2 large, distributed on the four sides outside the main building (the blue rectangles in the right side of Fig.1).

The envisaged muon detector is constituted by at least 4 tracking planes made with streamer tubes shielded by $\sim 1.5-2$ m of concrete in order to absorb particles with energy lower than ≈ 1 GeV, which could be reconstructed as punch-through tracks. On the top a layer of RPCs will image the electromagnetic component of the related showers.

SENSITIVITY TO γ-RAY SOURCES

In Fig.2 the red curve (1) shows the ARGO-YBJ Minimum Detectable Flux (MDF), at 5 standard deviation in one year of observation, for a Crab-like source with the experimental layout actually under construction (shown in Fig.1, left side).

The daily rate of events from the source has been evaluated by simulating a γ-ray flux according to the Crab Nebula spectrum dN/dE = $3.2\cdot\ 10^{-7}\cdot E^{-2.49}$ photons m^{-2} s^{-1} TeV^{-1}, measured by the Whipple collaboration [6]. The γ-rays have been simulated at different zenith angles, following the daily path of the source in the sky. At the Yangbajing site (latitude = 30° N) the Crab Nebula culminates at zenith angle $\theta = 8.1^\circ$. We "followed" the source up to $\theta = 40^\circ$, for a total observation time of 5.9 hours per day. In order to evaluate the background rate due to cosmic rays, we have taken into account the proton and helium fluxes, according to the spectra dN/dE = 8.98$\cdot 10^{-2} \cdot E^{-2.74}$ protons m^{-2} s^{-1} sr^{-1} TeV^{-1} and dN/dE = 7.01$\cdot$ $10^{-2} E^{-2.64}$ helium nuclei m^{-2} s^{-1} sr^{-1} TeV^{-1} [7]. In a first approximation the contribution of heavier nuclei can be neglected. The shower development in the atmosphere has been simulated by means of the Corsika code [8] and the response of the detector has been taken into account by using a GEANT3-based code.

For showers with a number of fired pads $N_{pad} \geq 50$, the position of the core is reconstructed and the arrival direction evaluated by a space-time conical fit to the shower front [9]. Only the events whose reconstructed core falls inside a "fiducial area" $A_{fid} = 80 \times 80$ m^2 (centered on the detector) are considered in the analysis, since the determination of the arrival direction is less accurate for external events. For events with a number of fired pads $30 \leq N_{pad} < 50$, the core reconstruction is less reliable, hence the shower front has been fitted to a simple plane.

We find that ARGO-YBJ can observe in one year a source (with a Crab-like energy spectrum) with a flux equal to 0.7 (0.4) Crab units, at energies E > 0.5 (1.0) TeV, with a significance of 4 standard deviations [10].

A similar calculation for an extended carpet is also shown in Fig.2 (green curve (2)). In this case the events have been reconstructed inside a fiducial area $A_{fid} = 100 \times 100$ m^2. The ARGO-YBJ sensitivity improves by a factor ~ 1.5 (~ 1.7) at 1 (10) TeV. We note that both these results have been obtained without any γ/hadron discrimination.

As previously discussed, the sensitivity of an EAS array can be improved rejecting the cosmic ray isotropic background on the basis of the muon content of triggered EASs. In comparison with hadronic showers, the muon content distribution of γ-induced events is significantly shifted toward lower values of N$_\mu$ and includes a much larger fraction of events with no muons detected. Therefore, we define as *muon-poor* those events that have a value of N$_\mu$ less than a value chosen to optimize the sensitivity to γ-ray sources. In oder to evaluate the improvement due to the presence of a muon detector, we calculate the so-called *"Q-factor value"* $Q_f = \frac{\varepsilon_\gamma(r_p)}{\sqrt{1-r_p}}$, where r_p is the fraction of cosmic ray background rejected with a given N$_\mu$ cut and $\varepsilon_\gamma(r_p)$ is the fraction of γ-induced showers which survives to this cut.

In Fig.3 we show the Q-factor values as a function of pad multiplicity for different N$_\mu$ cuts and for the two muon detector layouts investigated (left plot: 1440 m^2, right plot: 2500 m^2). As expected, the Q-factor improves lowering the cut value and increasing the detector area. 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 consider that only the showers with < 3 muons on the detectors are due to a γ-ray signal. The results of these calculations are shown in Fig.2 by the fuchsia and grey curves ((3) for 1440 m^2 and (4) for 2500 m^2, respectively).

At 30 TeV the improvement in the MDF, due to the rejection of showers with ≥ 3 detected muons, is a factor 6 (1440 m^2) or 10 (2500 m^2).

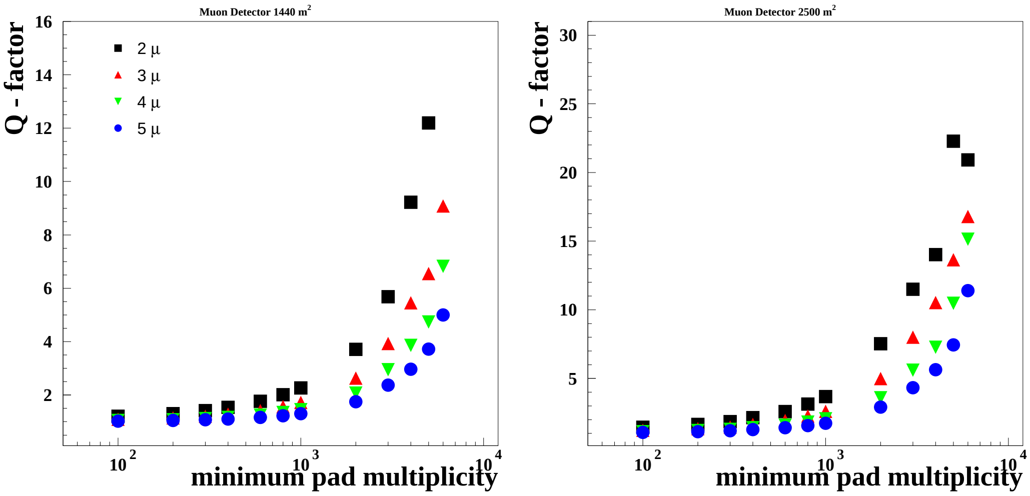

FIGURE 3. Q-factor vs. minimum pad multiplicity for different cuts (2, 3, 4, 5 μ). The left plot refers to a 1440 m^2 muon detector, the right one to 2500 m^2.

The rejection power for diffuse γ-rays

An isotropic diffuse flux of UHE photons is expected from the interaction of extra-galactic cosmic rays with the 2.7° background radiation [11]. The detection of the signal, however, 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 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 detector 2500 m^2 large, 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 panels 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 left plots refer to showers with $N_{pad} \geq 9000$ (photon median energy ~ 110 TeV), the right one to events with $N_{pad} \geq 13000$ (photon median energy ~ 150 TeV). As can be seen, the separation between photon- and proton-induced showers improves when the shower size cut is increased. We have conservatively fitted the proton distribution overestimating the background in order to predict their level at very low muon content [12].

The implications for γ-ray detection are tabulated in Table 1 for showers with $N_{pad} \geq$ 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 ~ 150 TeV energy can be

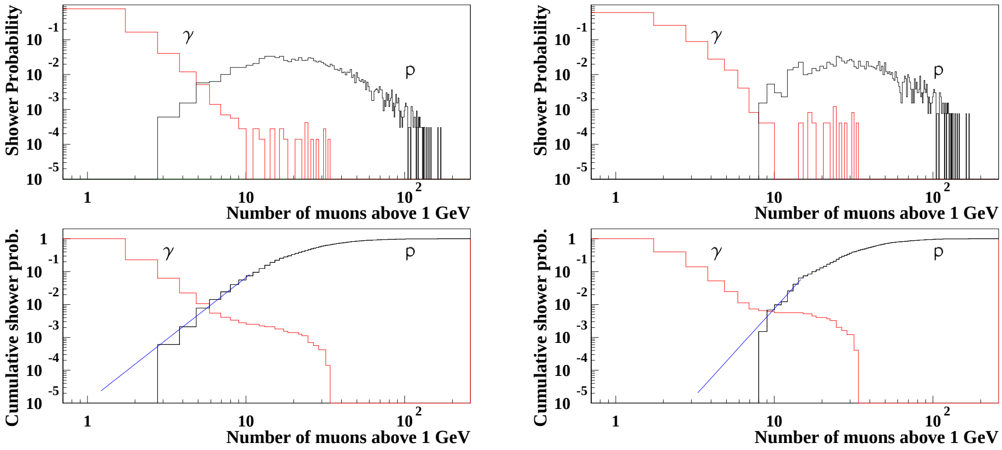

FIGURE 4. (a) Probability that a photon or proton shower generates a given number of muons. (b) Inclusive probability for the histogram shown in (a). The left plot refers to showers with $N_{pad} \geq 9000$, the right one to $N_{pad} \geq 13000$.

TABLE 1.

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

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.

REFERENCES

1. Di Sciascio, G., *"Status of the ARGO-YBJ experiment"*, these proceedings.
2. Aharonian, F. et al. A&A 390 (2002) 39.
3. Alexandreas, D.E. et al. ApJ 383 (1991) L53.
4. McKay, T. et al. ApJ 417 (1993) 742.
5. Aharonian, F. et al. astro-ph/0407118.
6. Hillas, A.M. et al., ApJ 503 (1998) p. 744.
7. Gaisser, T.K. et al., Proc. 27th ICRC, Hamburg (2001) p. 1643.
8. Heck, D. et al., Report FZKA 6019 Forschungszentrum Karlsruhe, 1998.
9. Di Sciascio, G. and Rossi, E., astro-ph/0309108 and astro-ph/0309109.
10. Vernetto, S. et al., Proc. 28th ICRC, Tsukuba (2003), p. 3007.
11. Halzen, F. et al., Phys. Rev. D41 (1990) p. 342.
12. Gaisser, T.K. et al., Phys. Rev. D43 (1991) p. 314.