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Based on the ultra-fast timing single muon tagging in atmospheric air Cherenkov imaging gamma ray telescopes

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Triggers from the so-called single muon events are an unwanted background for atmospheric air Cherenkov telescopes, degrading their sensitivity. That background is relatively unimportant at TeV energies but it is strongly increasing when upgrading the photon sensitivity of telescopes (either by increasing reflector area and/or by using light sensors of higher sensitivity) and lowering their threshold below a few hundred GeV. From general considerations one can anticipate that the signature of muons should be a narrow light pulse. In fact simulations show that light pulses from muons have very narrow time profiles, well below the time resolutions of most currently operating telescopes. In this report we elaborate on the time profile of light from the so-called single muons and show that a telescope with ultra-fast time response can open a new dimension allowing one to tag and to reject muon events.

1. Introduction

The first observation of γ- rays from the Crab Nebula by the Whipple experiment in 1989 [1] started a new part of gamma - astronomy based experiments measuring the Cherenkov light produced by the atmosphere excited by charged energetic particles of a shower. By the air Cherenkov telescopes (IACT) technique we analyze images of showers formed on the telescope camera. The last generation of IACT [2] [3] [4] [5] has been doing effort to lower the energy threshold to obtain spectra of the sources also below 100 GeV. Larger mirrors have been build, more sensitive PMT and faster readout systems used. Unfortunately a larger mirror's area may be the main reason of an additional problem of the so-called muon events. These are produced by a single particle, when the Cherenkov photon density on the ground is high enough to trigger the telescope. A telescope has limited area and field of view (FOV) so that only a part of full muon track can be seen. Other charge particles e.g. a hadron or electron and from a shower may also be observed as muon events if the length of their track is long enough. The simulations for MAGIC telescope [5] show that in an average shower the rate of the number of photons produced by hadrons to the number of photons coming from muons is 0.1. Additionally we have checked in the simulations that around 30 percent of triggered proton events have images mostly done by light from muons in comparison with 0.4 percent of events containing major part of photons from hadrons. We conclude that single particle events have mostly muon origin.

How many muons in a shower may be a source of muon events in IACT? To estimate this number we made MC simulation using CORSIKA code version 6.023 [6] for fixed primary energy protons: 50 GeV, 100 GeV, 300 GeV and 500 GeV at zenith 0^o and we found out that the average numbers of muons (with energy above Cherenkov threshold) are 0.09, 0.36, 1.89 and 3.44 respectively. Not all of these muons may be observed as muon events, at higher primary energy they mostly give a contribution to the image together with the rest of the particles, but still one may find a separated muon at a distance of 1 km from the shower axis. We also should remember that a muon passing the atmosphere changes its direction due to the multiscattering effect and magnetic field influence.

The shape of a muon image depends on its energy, impact parameter and incident angle [7]. If a muon parallel to the telescope axis, hits the detector or the area close to the reflector then we may recognize it in the data as an arc or a full ring image. For larger distances the situation is more complicated because the images

are similar to the γ - induced events; they have quite narrow ellipsoidal shape with longer axis directed to the center of the camera. As one may expect muons coming almost isotropically within the camera FOV, so the orientations of the ellipses should be random. In case of muons close to the telescope axis the classical gamma/hadron separation [8] (cuts on the Hillas parameter) does not work effectively and a new method is needed. Calculations show that the time delay of Cherenkov photons (in reference to the first one hitting a ground) depends on the height of their production. For example all photons from a 100 GeV muon come to the telescope level (say at 2200 m) within 6 ns and the light is created everywhere below 45 km a.s.l.. We may expect a much narrower arrival time distribution as we collect the light only from a part of the track due to the telescope's geometry.
There are two classes of reflector shape used in IACTs:

1. a Cotton-Devis design
2. with parabolic main shape.

The first one is designed to decrease the spherical aberration, but it widens the arrival time distribution of Cherenkov photons and it cannot be used for our purpose. The second one keeps the time distribution almost unchanged, but it gives non-negligible aberration. In this paper we show the idea of tagging single muons in IACT with a parabolic reflector.

2. Discussion

We have used the CORSIKA code version 6.023 [6] to simulate shower development in the atmosphere for different primary particles: γ, protons and muons. The total number of proton-induced showers was 750000 with the energy between 40 GeV and 30 TeV, the slope of differential spectrum -2.75, impact parameter up to 300 m and the direction of the showers was simulated in the view cone of 2.5^o around the position: 20^o zenith and 0^o azimuth angles (the shower axis points to the North). In case of γ cascades we have simulated 350000 events with the energy between 10 GeV and 30 TeV with the slope of the spectrum -2.6, impact parameter up to 300 m and the fixed direction: 20^o zenith and 0^o azimuth. For muons we have used the slope of the spectrum -2.69, energy range from 10 GeV up to 100 GeV, impact parameter up to 200 m, the direction in the view cone of 1.2 degree around the same position. The total number of the simulated muon tracks is 400000 events. We fixed the starting point in the atmosphere at the level 100 g/cm^2 (around 17km a.s.l.). Our telescope was MAGIC-like [5], so it has the same position on the Earth, the same area and the same geometry. First we have looked at the Cherenkov photon arrival time distributions on the camera plane for all events, with more than 200 photons after atmospheric absorption. The results are shown in Figure 1 and it can be seen that in the case of primary muons the distribution is really very narrow and the peak structure for small times in case of primary proton is due to individual muons (no Cherenkov photon on the camera from other secondary particles appears).

We have also calculated the RMS of the arrival time distribution in each individual event and the results show very good gamma/muon separation. In reality the measured pulses are convolutions of the arrival time distribution and the light sensor response. In the next step we have supposed ultra fast PMT may give us the pulse with the rise and fall time 0.6 ns and 0.7 ns correspondingly and FWHM = 1 ns from one photoelectron. Additionally we have added a jitter of electronic system as a gaussian shape with $\sigma = 300ps.$. The trigger condition, 4 next neighbouring pixels above the threshold, have been adopted in the simulations to reject all events not registered. The distributions of the RMS obtained pulses in each triggered event are shown in Figure2.

It maybe concluded from this plot: the RMS of the pulse below 0.7 ns indicates that the image corresponds to

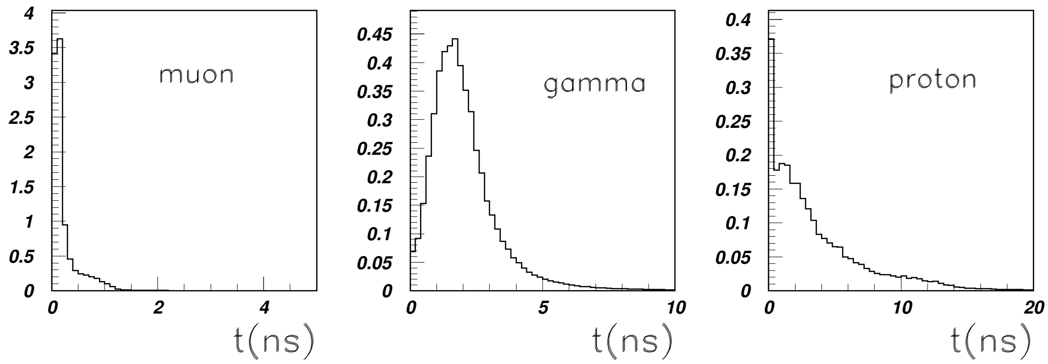

Figure 1. Arrival time distributions of Cherenkov photons on the camera plane for different primaries. All distributions are normalized to 1.

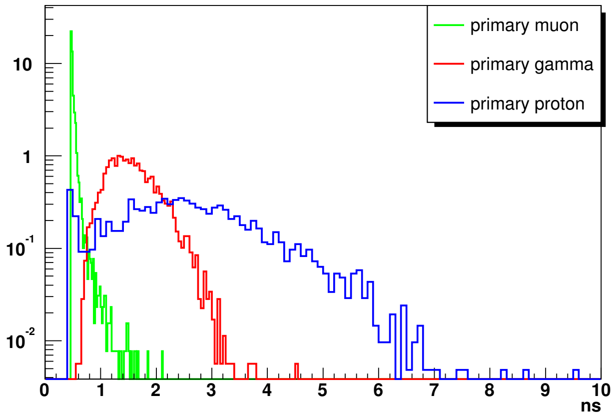

Figure 2. The RMS of the pulses after jitter and PMT simulations for triggered events only. All distributions are normalized to 1.

one charge particle (like a muon) and also almost all the pulses with RMS larger than 3.5 ns have a hadronic origin. Using very fast readout system (at least 2 GHz FADC) one could make a not negligible background reduction without any additional image parameters. It is interesting to see how the widths of the pulse depend on the image sizes. We plotted it for primary gammas and muons in Figure 3a and one may say that images of one muon track contained relatively small number of photoelectrons and a small overlapping region between two primaries is connected with low size images.

One may also try to check if the images with small RMS can survive the standard γ/hadron separation. Figure 3b shows the same as Figure 3a but after some statical cuts on length, width, distance and alpha parameters.

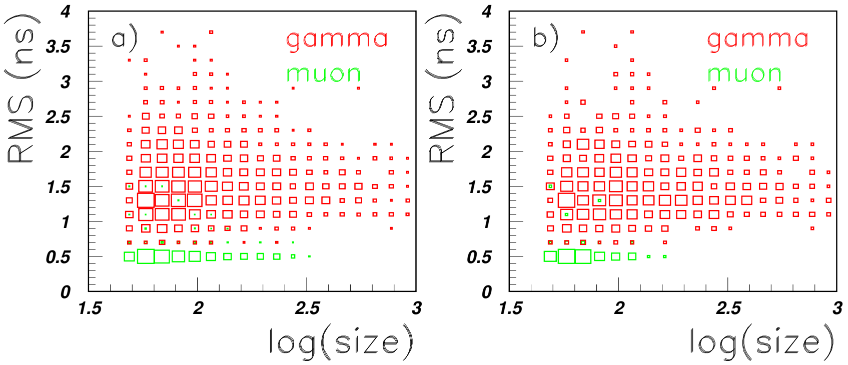

Figure 3. The RMS of the pulses versus log(size) for primary muon and γ

There are still muon events after this procedure. The same was done for primary proton and as was expected some events with small RMS were not excluded as γ candidates.

3. Conclusions

If the PMTs are as it was simulated in this work then one should use 2 GHz or faster FADC to reconstruct a very narrow signal from single particle events (at least 3-4 point sampling is needed). An IACT with large area of reflector collects a larger background from muon events, but there is a method of suppressing them by using ultra fast light sensor and ultra fast readout system.

4. Acknowledgements

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