# Isolated Muon Study for the MAGIC Telescope

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## Abstract

MAGIC is the worldwide largest air Cherenkov telescope, designed to detect gamma rays above an energy threshold of 10-30 GeV [2, 3]. In the energy region below 100 GeV because of the large mirror area and high photon sensitivity, one expects intense backgrounds from local muons and electrons along with the light of the night sky and the star light. Muon images sometimes can mimic gammas. In order to achieve the maximum sensitivity for MAGIC, it is important to understand the characteristics of the muon background. In this paper we will present Monte-Carlo based studies of muon images.

## 1. Introduction

Due to high light sensitivity MAGIC will detect the Cherenkov light from single muon high up in the atmosphere and up to the edge of the Cherenkov light pool (∼120 m). Therefore a large number of muon triggers is expected. The image of a muon is determined by its impact parameter (distance to the muon trajectory from the telescope), angle of incidence, the energy as well as by the optical aberrations of the reflector. Especially, the impact parameter plays an important role(discussed later). Muons whose impact parameter is large make arc images on the camera plane. The arc may resemble a gamma shower. Sometimes muons have relatively large deviation from the parent hadron shower axis and can thus appear in the field of view of the telescope, in the absence of the hadron images, as isolated particles and because of high photon density they can trigger. Therefore, the so-called isolated muon, can become a serious background and deteriorate the sensitivity of the telescope. In addition, the trigger of a single muon can clog the readout system and increase the dead time. However, muons can also be useful to calibrate the photon sensitivity of the telescope. The amount of light along the ring (or arc) per length is almost constant because of azimuthal

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symmetry of the emitted Cherenkov light. Using this feature, one can perform an absolute calibration of the whole telescope [4, 5].

## 2. Methods

To investigate the characteristics of muon, firstly, proton and gamma showers are simulated with the air shower simulation program CORSIKA (ver. 6.0.19). The total number of simulated events is 9 million protons and 2 million gammas. The energy range is from 30 GeV to 30 TeV for protons and from 10 GeV to 30 TeV for gammas. For gammas the zenith angle is fixed to 0 degree. For the proton showers their directions are chosen isotropic within 6 degrees radius around the fixed zenith. The distribution of the shower core positions is isotropic within a circle of 400 m for the proton showers, and 300 m radius for the gamma showers around the telescope. The differential slope of the energy spectrum is -2.7 for proton showers, and -2.5 for gamma showers. The simulated data is passed through a simulation of the reflector and a 1141-pixel camera program. In the reflector program, the Cherenkov photons that are simulated with CORSIKA are traced to a camera plane with realistic mirror configuration. In the camera program, the photons are collected onto photo multipliers and subsequently converted into photo electrons (phe). The light of the night sky is added, assuming a mean value of 0.5 phe per 3.3 ns (corresponding to 1 FADC sample) according to a Poisson distribution. Then the events that fulfill a trigger condition of compact adjacent 4 pixels in the $\sim 0.96°$ radius with a signal larger than 5 phe's are selected. After this procedure, image cleaning is applied. The cleaning procedure is the following: first, pixels whose signal are larger than 4 phe's are selected and then the surrounding pixels whose signal are above 3 phe's are also selected. Finally, among all these, only those pixels at least two neighbors are kept. After this cleaning, the image parameters of Hillas [6] are calculated.

## 3. Results and Discussion

4.2 % of the simulated gammas gave triggers, while only 0.22 % of protons did. A distribution of the ratio of the light in the camera coming from a muon to the total collected light for proton showers is shown in Fig.1. Mainly two components can be seen. One is the component near 1 which is mainly due to isolated muons. The other component near 0 is the one from only electrons. There are small contributions from other particle, such as pions and kaons, but they are negligible ($\sim$ 1 %). Here, we want to discuss about isolated muons and therefore we define a muon event as one whose light ratio to the total is larger than 0.9 ($\sim$ 18% of the triggered proton events). Later on these events are treated as (isolated) muons. With these muons, we calculated a trigger rate of the isolated muons by using the proton flux [1]. A rate of $51 \pm 22$ Hz is obtained.

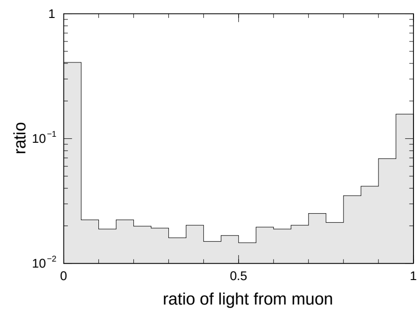


**Fig. 1.** Distribution of the ratio of the light in the camera coming from a muon to total collected light for proton showers. The number in each bin is normalized to the total number of events.

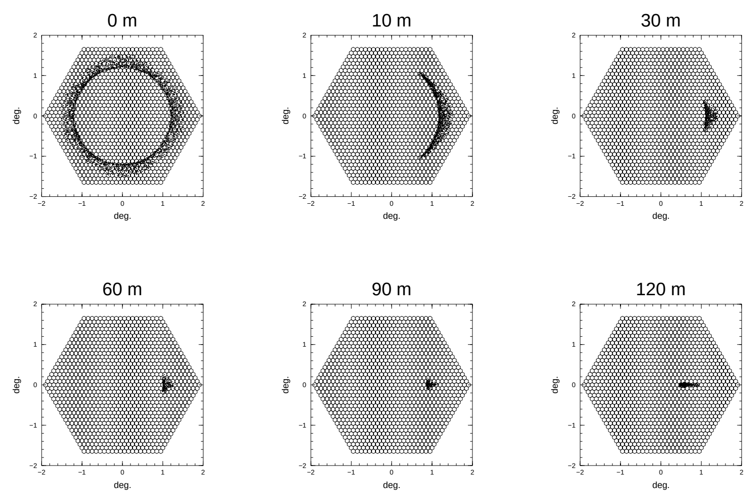


**Fig. 2.** Single muon image dependence on the impact parameter. The images of muons coming parallel to the axis of the telescopes are shown for impact parameter values 0m, 10m, 30m, 60m, 90m and 120m respectively.

Images of single muons for different impact parameters are shown in Fig.2. As the impact parameter increases, the image size shrinks. It is interesting to note that in the impact parameter range of 120 m the image of a muon elongates in the direction perpendicular to the direction of the arc seen at lower impact parameters. This is a muon which is traveling a large distance high up in the atmosphere where the Cherenkov angle change is big and the length of the image is reflecting of variation of the Cherenkov angle. Note that in reality the muons are coming isotropically and the above shown images change their orientation. Short muon arcs can sometime mimic gammas. In Fig.3. a scatter plot of the image parameters SIZE versus LENGTH for gammas and muons generated in proton showers are shown. To obtain reliable results, SIZE (total number of phe) and DISTANCE cuts are applied. The condition is that SIZE $\geq 60$ phe's and $0.4^\circ <$ DISTANCE $< 0.9^\circ$. The amount of light from a muon is almost constant along

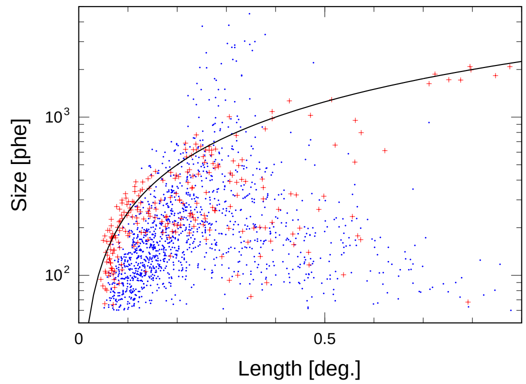


**Fig. 3.** A scatter plot of the image parameter SIZE versus LENGTH. Dots and crosses denote gamma showers and isolated muon images respectively.

its image length. The LENGTH and the SIZE have a strong correlation as one can see in the Fig.3. Nevertheless, because there can be two or more muons in the image simultaneously, some muons rule out this relation. By investigating islands on the images made by muons, the background may be effectively separated from gammas. If the impact parameter smaller than a mirror radius, the ring image is largely in the camera and can be seen as such in Fig.2. (top left). One can easily identify these rings because they have well-defined curvature. Up to an impact parameter of 20 m the arc shape (see, for example, Fig.2. top center) can be distinguished, and this information will be useful to separate gammas from muons. On the other hand, concerning the events whose impact parameter is larger than $\sim$ 70 m, their images are very small but the photon density is high in the image. For these events the LENGTH is less than $\sim$ 0.1 degree in Fig.3.. As one can see, such a muon can be distinguished from gammas. Muons which are difficult to distinguish are those with impact parameters in the range $\sim 20-50m$ As seen in the figure, gamma and muon images are overlapping from 200 phe's to 700 phe's. This corresponds to roughly the energy range of gammas from 50 GeV to 180 GeV.

In order to reject more muons, other Hillas parameters, such as CONCENTRATION, ASYMMETRY and more, are under test. Also multiple muon study is an important issue for the reasons pointed out above. Further investigation will be performed.

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