IOP Conf. Series: Journal of Physics: Conf. Series **876** (2017) 012023 doi:10.1088/1742-6596/876/1/012023

Muon study for gamma/hadron air-shower discrimination in the HAWC observatory

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Abstract. The High-Altitude Water Cherenkov observatory is a ground-based array designed to study energetic gamma-rays. Experiments with this purpose have to face a huge rate of undesired hadronic background. Motivated by the fact that muon content is quite different in gamma-induced (poor in muons) and hadronic-induced (rich in muons) air-showers, we study the idea of formulating a new variable for background reduction related with counting the number of muons candidates present in such showers. Therefore, in this work we used the time differences between photomultipliers tubes to identify the signature of muons inside the water Cherenkov detectors. Showers with a high presence of muons typically must produce a characteristic time difference around 5 ns among the central detector (PMT_C) and each one of the laterals (PMT: A, B, D).

1. Introduction

Gamma-rays are the most energetic radiation of the electromagnetic spectrum. There are extreme environments in the Universe (e.g. Supernova Remnants, Active Galactic Nuclei, Gamma-Ray Bursts) which emit gamma-rays with energies in the range of GeV-TeV (Very High Energy-VHE domain). These gamma-photons are the result of electromagnetic or hadronic processes and can travel from the source to the Earth without being deflected by cosmic magnetic fields, therefore making them suitable for performing astronomy. Because the Earth´s atmosphere is opaque to photons beyond the optical waveband, VHE gamma-rays can be indirectly detected with ground-based telescopes. When a gamma-ray interact high in the atmosphere it produces a cascade of secondary relativistic particles known as an Extensive Air Shower (EAS). An air-shower is accompanied by radiation emission like: Cherenkov light, fluorescence and radio bursts. Observatories focus mainly in gamma-induced air-showers, make use of the Cherenkov effect in both: air and water. Imaging Atmospheric Cherenkov Telescopes (IACTs) collect this light with mirrors and reflect it toward sensitive cameras, producing as a result an image of the shower. Depending of the image´s shape it can be identified as gamma-initiated showers and also to estimate their energy and direction. Other technique, employed by surface array telescopes, consist in detecting the light generated when charged particles of the shower enter inside water reservoirs. A common issue of these experiments is dealing with a large background originated by hadronic primary cosmic rays. Such “noise” can be thousands of times greater than gamma signals (in HAWC is ~ 24 kHz [1]), then new methods for gamma/hadron separations are needed. The muon content of the showers could be a good discrimination parameter, because gamma showers are purely electromagnetic and contain few muons. In order to help the noise reduction in HAWC, this work aim on identifying muons signals in data using only times measurements.

2. The High-Altitude Water Cherenkov observatory

The High-Altitude Water Cherenkov (HAWC) observatory is a facility conceived to study gamma-rays with energies between 100 GeV and 100 TeV. It is located 4100 m a.s.l on the flanks of the Sierra Negra volcano near Puebla, Mexico. The detector is an array of 300 Water Cherenkov Detectors (WCD) or tanks, each one with 4.5 m high, 7.3 m diameter and a volume that contains 200 000 L of purified water. There are four photomultiplier tubes (PMTs) positioned in the tank base: a high-quantum efficiency detector or PMT_C (10-inch diameter) centrally located, surrounded by three (8-inch diameter) PMTs (A, B, D); all upward facing (Fig. 1). With an instantaneous field of view of 2 sr, HAWC observes two-thirds of the sky during each 24-hour period in the Northern Hemisphere [2].

2.1. HAWC operating principle

The HAWC array is used to sample air-shower particles by recording the Cherenkov light produced when they pass through tanks full of water. This electromagnetic radiation is emitted into a forward cone that surrounds the direction of motion of the charged particle. The opening angle of the cone depends on the index of refraction (n) of the medium, in water (where n = 1.33) the angle is ≈ 41°. Because the Cherenkov cone in water is so large, nearly every charged particle that enters the tank should be observed by at least one of the four PMTs, which convert the light into an electrical signal measurable by the data acquisition system. The output data correspond to charge and time of triggered PMTs, later used for the shower´s parameters reconstruction (e.g. core position, arrival direction, energy, event classification: gamma or hadron).

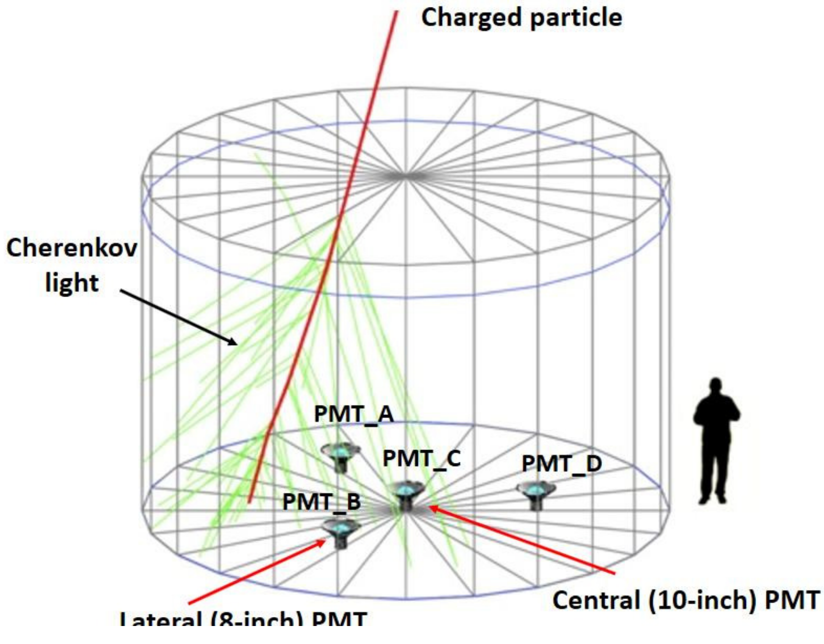

Figure 1. WCD setup, where the passage of a charged particle emitting Cherenkov photons is illustrated.

3. Muon candidates in HAWC raw data

Muons are the most abundant charged particle at the HAWC altitude and arrive mainly with some GeV of energy. They are originated from charged meson decays (π, K) in EAS, following approximately straight trajectories through the atmosphere and even inside WCD. Depending on the area where a muon travels it can trigger a specific number of PMTs, this is called multiplicity (M).
In this work we used a sample of raw data. This refers to the processed signal of PMTs before the multiplicity trigger threshold for events selection is applied. In order to detect muon candidates in raw data, we analysed tanks with four-folds (M = 4) in a very short time window. This selection can include electrons which trigger as well all 4-PMTs inside a WCD, but there is a specific difference in relation to the time of detection they produce.

3.1. Simulations to compare with selected data

Regarding vertical muons with trajectories close to the central light-sensor, in [3] it was analytically calculated a characteristic time difference (≈ 5.4 ns) between the PMT_C relative to the peripheral ones. With the aim of comparing the time differences distributions obtained in raw data sample, we performed Monte Carlo simulations (MCsim) of vertical muons and electrons in a single tank (Fig. 2).

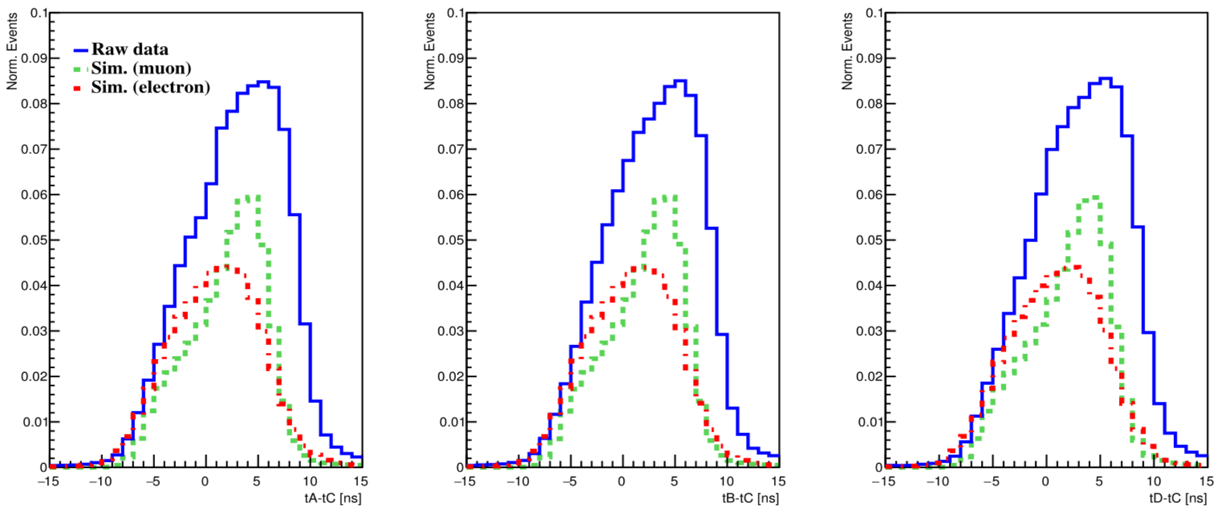

Figure 2. Comparison of the time difference distributions between PMTs for vertical electrons (red) / muons (green) and raw data (blue).

In the simulation we set the following energy for particles: electrons with 1 - 500 MeV and muons with 15 GeV. Data selection was in tanks with M = 4 within 15 ns window. Fig. 2 show that raw data and vertical muon distributions present a similar shape, proving that time difference (PMT_laterals – PMT_C) has a mean value of approximately 5 ns. However, electron distribution is quite different with a time difference average value near 0 ns, meaning that the PMTs see the Cherenkov light practically at the same time. This happens because electrons stop quickly in the first centimetres of the tank and then the light travels to the bottom falling promptly over all the detectors. On the other hand, muons reach the tank floor triggering the PMT_C first, and later the light arrive to the lateral PMTs.

4. Time difference analysis in shower data

Like gamma showers are mainly electromagnetic (containing a lot of e-, e+ and γ), they must exhibit a time difference close to 0 ns. In order to test this hypothesis, we used MCsim data of gamma-induced showers created by the HAWC software and real shower data which passed the trigger condition.

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Figure 3 shows distributions produced by showers with unequal muon content. The shower data is rich in muons, this is the reason why the time differences tends to approximately 5 ns.

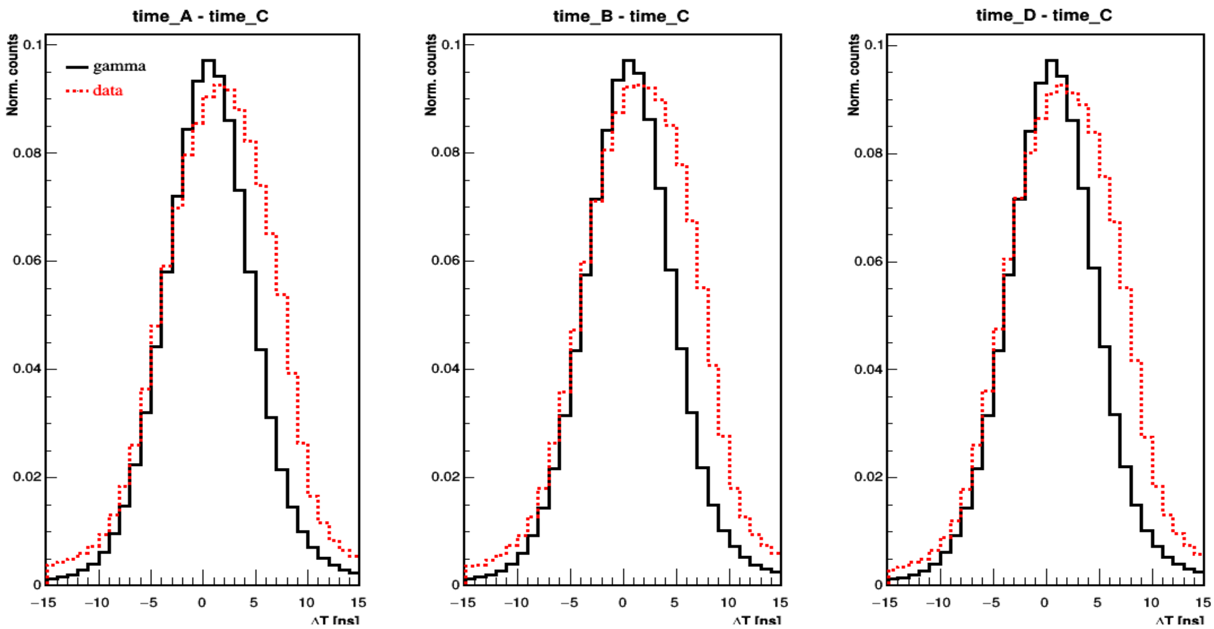

Figure 3. Comparison, using time difference distributions, of shower data (red) vs gamma MCsim (black) for tanks with multiplicity 4.

An overlap of both data can be seen in Fig. 4, that was created using two time differences. It is evident the spreading of shower data toward large time values. Each point represents a tank with M = 4. Figure 5 include charge information for a pair of PMTs used in a time difference. Most of the values are displaced to left side as a consequence of central PMT higher sensitivity.

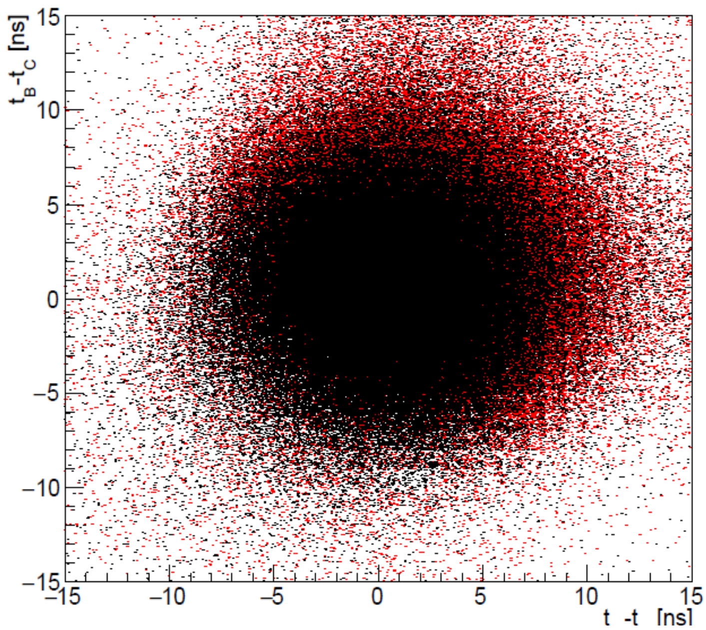

Figure 4. 2D plot with two time differences corresponding to gamma MCsim data (black points) and shower data (red points).

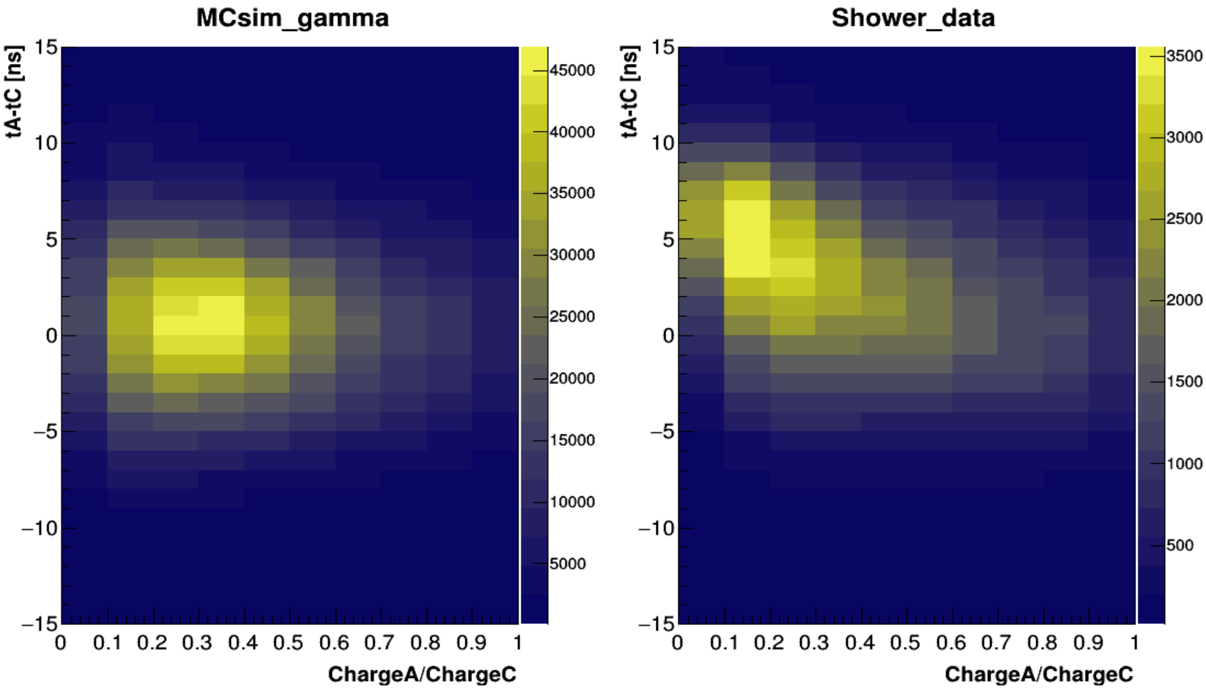

Figure 5. Comparison of 2D plots built with a time difference and the corresponding charge ratio, for gamma MCsim and shower data.

5. Remarks and future work

- Muon candidates are detected in HAWC data with a characteristic time difference close to 5 ns which is different for electrons.
- There is a separation between the time difference distributions for gamma MCsim and the shower data, due to the unequal muons content.

The future work is to create a discrimination variable that consider the number of muons in a shower. One muon candidate will be selected using the restriction r_time > 7 ns, where r_time is presented in equation (1). Such cut allows to obtain a higher discrimination power. Then, the number of muon candidates will be the sum of tanks with multiplicity 4 per event that satisfied the restriction, expecting larger number for hadronic showers.

$$r\_time = \sqrt{(tA - tC)^2 + (tB - tC)^2 + (tD - tC)^2} \quad (1)$$

Acknowledgments

We acknowledge the support from: US National Science Foundation (NSF); US Department of Energy Office of High-Energy Physics; The Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México; Red de Física de Altas Energías, México; and the University of Wisconsin Alumni Research Foundation.

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