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A fast muon tagger method for Imaging Atmospheric Cherenkov Telescopes

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Abstract. The Cherenkov Telescope Array (CTA) will be the next major observatory for Very High Energy gamma-ray astronomy. Its optical throughput calibration relies on muon Cherenkov rings. This work is aimed at developing a fast and efficient muon tagger at the camera level for the CTA telescopes. A novel technique to tag muons using the capabilities of silicon photomultiplier Compact High-Energy Camera CHEC-S, one of the design options for the camera of the small size telescopes, has been developed, studying and comparing different algorithms such as circle fitting with the Taubin method, machine learning using a neural network and simple pixel counting. Their performance in terms of efficiency and computation speed was investigated using simulations with varying levels of night sky background light. The application of the best performing method to the large size telescope camera has also been studied, to improve the speed of the muon preselection.

1. Introduction

The Cherenkov Telescope Array (CTA) will be the leading ground-based observatory for Very High Energy (VHE) gamma-ray astronomy for the next decades. The observatory will operate arrays on sites in both hemispheres to provide full sky coverage and will hence maximize the potential for investigating very energetic non-thermal cosmic accelerators such as supernova remnants, gamma-ray bursts or gravitational wave transients. Its southern and northern sites will host 99 and 19 telescopes respectively. CTA will operate in an energy range from a 20 GeV to 300 TeV. Wider field of view and improved sensitivity will enable CTA to survey hundreds of times faster than the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). The array will have telescopes with three different sizes specifically designed to cover different parts of the energy range. The Small Sized Telescopes (SSTs) with a primary mirror diameter of nearly 4 meters will cover the high energy range, the Medium Sized Telescopes (MSTs) with a diameter of 12 meters will cover the intermediate range and the Large Sized Telescopes (LSTs), that will be the largest telescopes, with a mirror diameter of 23 meters, will cover the lowest range [1].

Muons produced in Extensive Air Showers (EAS) are an important absolute calibration source

Figure 1. CHEC-S with a view onto the focal plane equipped with SiPMs [2].

for light throughput estimation of ground-based Cherenkov telescopes. Muons generate ring-like images in IACTs when traveling nearly parallel to the optical axis. From the geometrical parameters of these images, the absolute amount of light emitted may be calculated analytically. Comparing the amount of light recorded in these images to the expectation is a well-established technique for telescope optical efficiency calibration [4]. This work is aimed at developing a fast and efficient muon tagger at the camera level for the CTA telescopes. A novel technique to tag muons using the capabilities of the Compact High-Energy Camera CHEC-S, one of the design options for the camera of the SSTs, has been developed, studying and comparing different algorithms such as circle fitting with the Taubin method, machine learning using a neural network and simple pixel counting. Their performance in terms of efficiency and computation speed was investigated using simulations with varying levels of night sky background light. The application of the best performing method to the LST camera has also been studied, with the goal of improving the speed of the muon preselection.

2. Calibration of the optical efficiency with muons and muon tagging

Muons produced in EAS are relativistic and produce a cone of Cherenkov light with an angle of about 1.4° at sea level. Those hitting the telescope mirror are called *local muons* and they produce ring-like images in the telescope camera, see Fig. 2 (a) and 5. The light intensity can be computed analytically [4] and its comparison with the observed one and the geometrical parameters of the ring allow to evaluate the optical efficiency of the telescope. However IACT arrays typically only record events where at least two neighboring telescopes trigger are in coincidence, a technique which suppresses spurious events due to noise, but also local muons. Therefore, one of the requirements for the proposed cameras of CTA is to be able to trigger and record muons with high efficiency. The development of a fast muon tagging algorithm that operates at CameraServer level is necessary. The background for muon identification are EAS images. However, only proton shower images have a geometrical dimension and luminosity comparable to that of a local muon, see Fig. 2. Moreover, they have a higher rate with respect to electromagnetic showers, therefore other primary particle shower backgrounds will be neglected.

3. Muon tagging with CHEC

CHEC-S is a camera design for the Schwarzschild-Couder double-mirror telescopes [2]. It has 2048 6x6 mm pixels based on SiPM photosensors. The camera surface amounts to 30x30 cm^2. A dedicated ASIC (T5TEA, derived from TARGET 5 [3]) is responsible for the trigger formation comparing to a trigger threshold the sum of the signals of 4 adjacent pixels. These groups are called superpixels. This results in a 512-bit superpixel pattern, allowing to have low-resolution, black/white shower images at trigger level. This study [6] aimed at developing a technique to tag

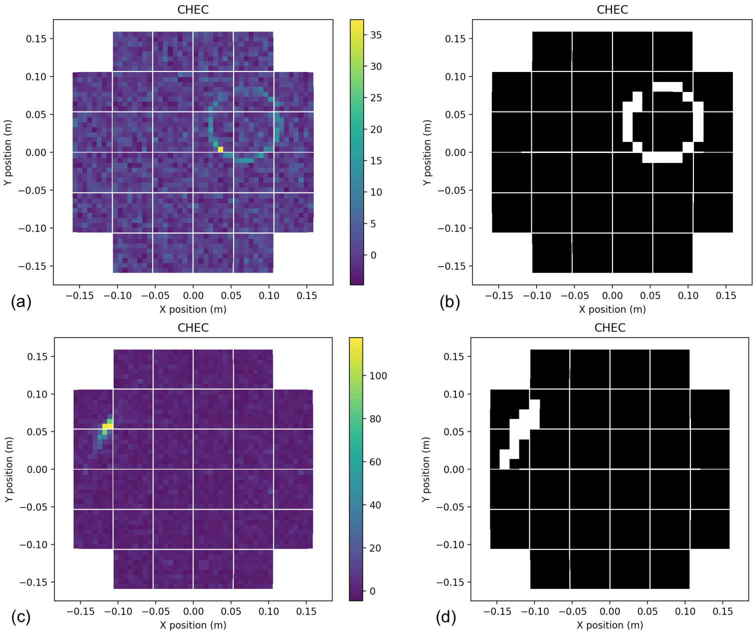

Figure 2. Examples of simulated events: The Cherenkov image in photoelectrons and its triggerpattern image respectively for a 22.69 GeV muon event (a) and (b) and a 5.41 TeV proton shower (c) and (d).

muons from these images, with enough performance in terms of speed and efficiency to meet the requirements established by CTA: to flag fully contained muon rings with an overall efficiency above 90 %. In Fig. 2 there are examples of simulated muon and proton shower images. For both events there is the full recorded Cherenkov image on the left and the corresponding superpixel trigger pattern on the right. We performed a preliminary study [6] on different algorithms to discriminate muons and protons testing speed and efficiency. The algorithms rely on the characteristic circular shape of the muon image. The following methods were tested:

- a circle fit procedure with the Taubin method [5],
- image recognition using a neural network (Multilayer Perceptron),
- Majority, setting a discrimination threshold on the number of fired superpixels.

In Tab. 1 the event processing rates for all methods are summarized. The expected CHEC-S readout rate is larger than 1 kHz, hence the method needs to match this speed. The majority classifier has revealed to be the best performing method and its extreme simplicity leads to an impressing computational speed, making it the ideal candidate to be implemented directly in the

Table 1. Average event processing rate of each method at 95% efficiency.

method	rate
Taubin	188 Hz
MLP	63 kHz
Majority	130 kHz

backplane of the camera. Therefore, more detailed studies were carried on. In Fig. 3 there are the muon signal and proton shower background distributions of the Majority method. Muons were simulated in an energy range from 8 GeV up to 1 TeV and protons from 1 to 300 TeV, both with a spectral index of $\gamma = -2.0$.

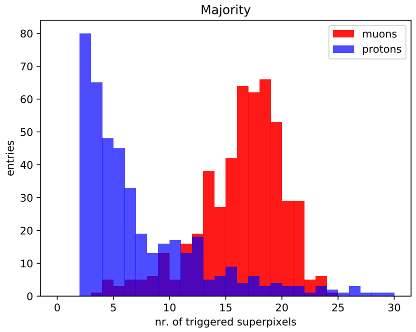

Figure 3. Superpixel distributions of muon signal and proton shower background with low NSB for CHEC.

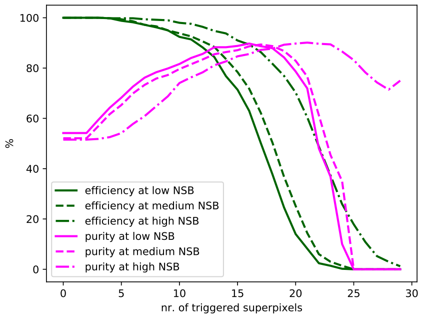

Figure 4. Selection efficiency and purity plots for different NSB levels for CHEC.

3.1. *Stability in terms of Night Sky Background*

An important element to consider when examining these methods, is the stability with changing Night Sky Background (NSB) [6]. Different NSBs are related to different observation regions. Standard simulations as considered in Fig. 2, are performed with low NSB, corresponding to observations in the extragalactic field. A medium NSB level corresponds to observations on the galactic plane and a high NSB to the galactic center. The selection efficiency can change accordingly. In case of very high NSB the trigger threshold is adjusted, but in principle the NSB level is unknown, therefore the stability of the efficiency in meeting the requirement with varying NSB is important. However, the Majority holds an overall efficiency larger than 90 % even at increasing NSB, fixing a threshold providing 90 % efficiency at low NSB. This is found studying simulations with different NSB levels (Fig. 4).

4. Muon tagging with LST

LST is equipped with LSTCam, that is quite different with respect to CHEC-S. It has 1855 hexagonal photomultiplier pixels with 5 cm linear size [7]. An example of simulated muons and protons seen with LST are shown in Fig. 5 and 6, respectively. The LST effective area is much larger than the SST one, therefore the muon event rate is sufficiently high so that a dedicated trigger would not be necessary. Muons for calibrations are searched in an offline analysis. This muon identification is done using a precise fitting procedure that evaluates also most of the optical efficiency parameters. The computational time cost of the application of this procedure to all events is huge, hence we applied the Majority method to identify potential muon candidates and perform the fitting procedure only on a limited number of images. The Majority method is applied in a slightly modified version: the discrimination threshold is set on the *size* of the image. The size is the sum of the photoelectron content of all pixels. The distributions of the size of simulated muons and protons and the efficiency and purity are displayed in Fig. 7 and 8. Muons were simulated in an energy range from 8 GeV up to 1 TeV and protons from 100 GeV to 300 TeV, both with a spectral index of $\gamma = -2.0$. Already at this preliminary level, the efficiency and purity are larger than 90% choosing a proper threshold.

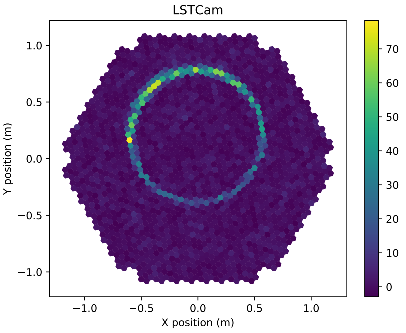

Figure 5. Cherenkov image in photoelectron of the simulation of a 42.01 GeV muon.

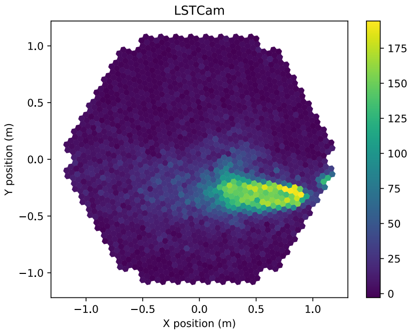

Figure 6. Cherenkov image in photoelectron of the simulation of a 1.76 TeV proton shower.

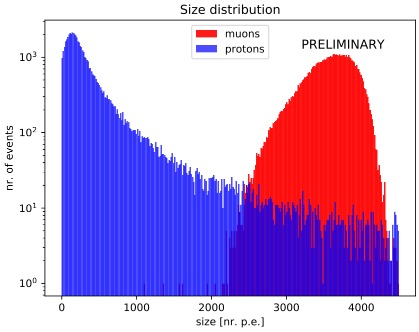

Figure 7. Size distributions of muon signal and proton shower background for LST.

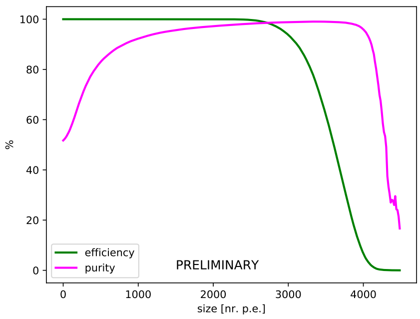

Figure 8. Selection efficiency and purity plots vs. size for LST.

The average event processing rate of the method on a simulation sample is

$$(27.477 \pm 0.001)\ \text{kHz}.$$

The preselection reduces the sample to 3.5% of the initial amount of events, and the fitting procedure to 0.5%, that are the useful muons. The computational advantage of applying the preselection is huge. The trigger rate of LST is about 10 kHz, therefore the preselection is more than compatible with the CameraServer speed. This opens a further possible application of this method to flag muons at CameraServer level.

5. Conclusions

In this contribution, we have presented the current status of the muon-tagging algorithm study for a muon trigger for CHEC-S and showed the first preliminary results obtained with simulations. We investigated different methods to tag muons from trigger-pattern images and we found that the Majority method seems to have the best performance in terms of speed, background rejection, and stability to increasing NSB. A deeper study of the efficiency of the Majority tagger is ongoing and the application on the CHEC-S prototype is foreseen. We have also presented the current status of the studies on the application of the Majority tagger for the offline muon preselection for LST. A more detailed efficiency and purity analysis is ongoing as well as tests on real data of the LST prototype.

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