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Reconstruction of truncated images for PeVatron searches with the Cherenkov Telescope Array

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Summary. — The Cherenkov Telescope Array (CTA) will be the future ground-based gamma-ray observatory using the imaging atmospheric Cherenkov technique. One of CTA's key science projects is the search for galactic PeVatrons, extreme sources of accelerating cosmic particles. CTA's sensitivity in the multi-TeV region is crucial for this goal. A dedicated reconstruction of the telescopes' truncated images has been implemented in the CTA reconstruction pipeline in order to optimize CTA's sensitivity at very high energies ($E > 10\,\mathrm{TeV}$). First results are presented together with perspectives for PeVatron searches with CTA-North array.

1. – Introduction

The origin of cosmic rays (CRs) is one of the open questions in astrophysics. Of particular interest in this field is the search for galactic PeVatrons which are sources capable of accelerating charged particles to at least $\sim$ PeV energies. If located in an environment particularly rich with matter, these sources are expected to be bright in the gamma-ray band with a spectral emission which extends beyond 100 TeV [1].

In order to efficiently detect gamma-rays in the multi-TeV region, large effective area detectors on the ground are needed. The Cherenkov Telescope Array (CTA) [2] will be the largest ground-based gamma-ray observatory using the imaging atmospheric Cherenkov technique. It is expected to cover a wide energy range from 30 GeV to 300 TeV with more than 100 telescopes distributed over two sites in the Northern and Southern hemispheres. In order to cover the entire energy range CTA will use three different types of telescopes: the Large, Medium and Small-Sized Telescopes (LSTs, MSTs and SSTs with mirrors of $\sim$ 23 m, 12 m, 4 m diameter, respectively). CTA-North is currently under construction and in this work we have investigated the possibility of optimizing its sensitivity for the observation of high energy sources and therefore for the PeVatrons hunt.

2. – Reconstruction with truncated images

Gamma-rays interacting with the atmosphere generate showers of charged particles responsible for the emission of flashes of Cherenkov light. This light is imaged using telescopes equipped with mirrors and cameras made up of photomultipliers. The position of the shower image and the amount of light recorded in the camera mainly depend on the energy of the primary particle and on the shower's impact point on the ground. When part of the shower falls outside the telescope's field of view, the image appears truncated as shown in fig. 1. An image is considered truncated if the position of its centroid is beyond the 80% of the camera radius, in this case it is rejected by the standard reconstruction. The present work aims to study the effect of including truncated images in the reconstruction pipeline of CTA and to quantify the possible benefit at high energies.

The simulation of the CTA-North baseline array (4 LSTs plus 15 MSTs) has been performed considering a point gamma-ray source observed at 20° zenith and 180° azimuth at the center of the field of view. Background events (protons and electrons) were also simulated. For the atmospheric showers and the detector response simulations the *CORSIKA* and the *sim_telarray* codes were employed [3].

The fundamental information provided by the reconstruction is the direction of the incoming primary particle, its energy and nature, whether gamma or background, expressed in terms of probability of being a gamma event. The reconstruction used in this analysis is based on *protopipe* [4] which is the prototype reconstruction pipeline of CTA, based on the *ctapipe* [5] library.

We have added to *protopipe* the possibility to process and parametrize truncated images. The showers' images are extracted considering the largest island of pixels above some threshold (typically a few photoelectrons) and parametrized using the Hillas parmeters [6] (see fig. 1(right)). The *standard method* for estimating the Hillas parameters is to calculating the moments of the 2D signal distribution using the "principal component analysis". For truncated images we have also implemented an *image-fitting method* based on a 2D Guassian fit of the shower image [7]. In this case, the largest island plus a crown of pixels around it is considered for the χ^2 minimization. The introduction of truncated images has required also a change of the Random Forest (RF) regressor used for the energy reconstruction. We have added the position of the centroid of the image as a new parameter of the RF. This change has also been applied to the reconstruction pipeline without truncated images. Only truncated images with at least

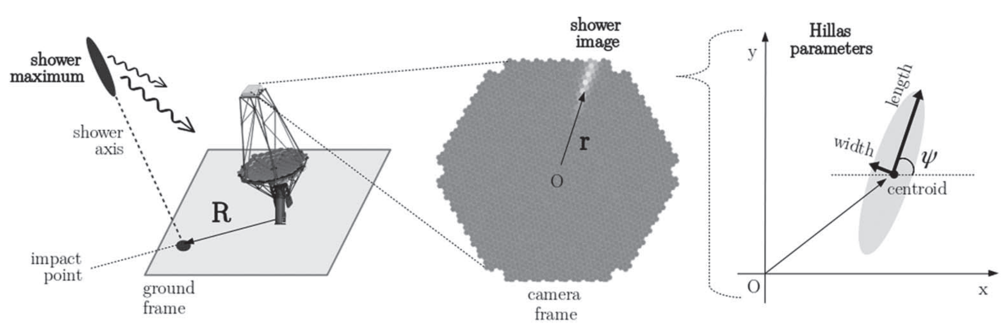

Fig. 1. – Showers at the border of the field of view of the telescope produce *truncated images*, *i.e.*, only partially contained in the camera. The sketch on the right shows some of the *Hillas parameters* used for the shower reconstruction.

10 pixels are considered. An event is reconstructed if it includes images from at least 3 telescopes.

3. – Results

In fig. 2(left) the impact points of the gamma events gained including truncated images are plotted on top of the CTA-North baseline array. We point out that the recovered events are mainly at $E > 10\,\mathrm{TeV}$ and fall outside the fingerprint of the array, thus at the edge of its field view. Figure 2(right) shows that including truncated images increases the collection area at high energies (by a factor 2 at 100 TeV). However, we observe also a degradation of the energy and angular resolution at high energies (about 40% and 80% respectively, at 100 TeV) due to the lower reconstruction quality of the truncated images. The differential sensitivity curve summarizes the overall performance of each analysis: it is defined as the minimum flux needed by CTA to obtain a 5 standard deviation detection of a point-like source in a certain observation time (here 50 h). We required at least 10 detected gamma-rays per energy bin and a signal/background ratio of at least 1/20.

Figure 3 shows the comparison between sensitivity curves corresponding to the analysis without and with truncated images analysed with the two Hillas parametrization methods. The sensitivities have been obtained for the CTA-North baseline array and for the CTA-North threshold array (4 LSTs plus 5 MSTs), which will be the array operating in the first phase of CTA. In the case of the baseline array, the gain in the collection area induced by the truncated images is not compensating the associated energy and angular resolution degradation, therefore we do not see an improvement of the sensitivity curve. Instead, for the threshold configuration, the higher fraction of reconstructed events at the border of the array leads to an improvement in sensitivity thanks to a higher gain in the collection area. The two methods for extracting the Hillas parameters give equivalent results.

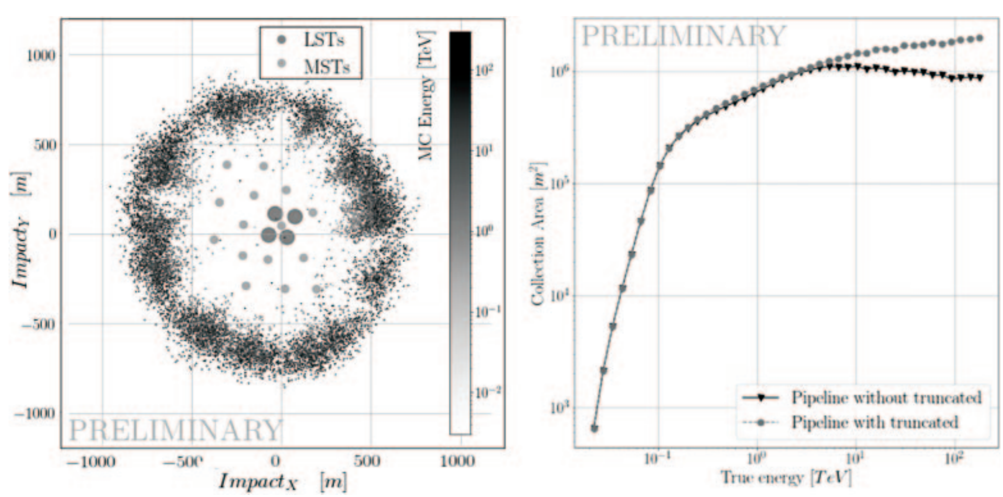

Fig. 2. – Left: top view of the CTA-North array and of the simulated impact points of the gamma events reconstructed including truncated images; right: comparison between the collection area obtained with and without truncated images.

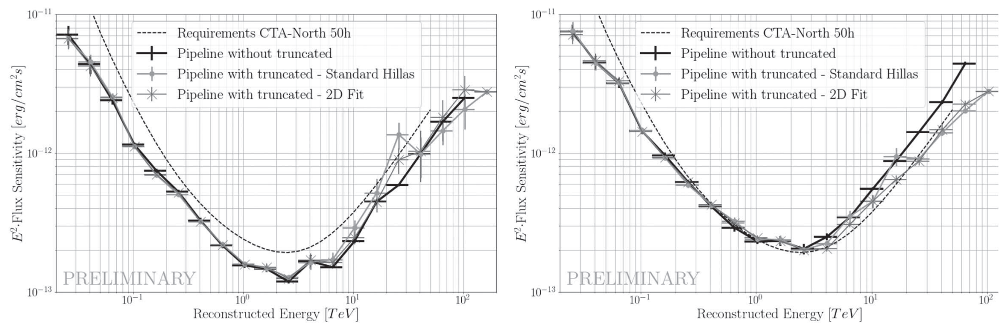

Fig. 3. – Sensitivity curves for the CTA-North baseline array (left) and the CTA-North threshold array (right). The dashed line shows the CTA-North sensitivity requirement. The error bars correspond to the simulation statistical uncertanties, propagated with the bootstrap method.

4. – Conclusions and outlook

In the present work we have investigated the effect of including truncated images in the reconstruction pipeline of CTA. In the case of truncated images, an alternative method for image parametrization, based on a 2D Gaussian fit, has been implemented and compared to the standard one. The study has been performed considering the CTA-North array, currently under construction, in the baseline (19 telescopes) and the threshold (9 telescopes) configuration. We have shown that including truncated images induces an increase of collection area mainly at high energies and that the recovered events are the ones falling at the border of the array. Smaller arrays thus benefit the most from truncated images' inclusion due to the higher border/surface ratio. We obtain an increase of sensitivity (above 10 TeV) in the case of a partially deployed CTA-North array, while no significant improvement is observed in the case of the final configuration. Events with truncated images may be includied in specific instrument response functions (IRFs) taking into account their lower reconstruction quality. They could then contribute to optimize the global IRFs for PeVatron searches. The proposed reconstruction could be particularly beneficial for the search of PeVatrons during the "early science" phase of CTA, which employs only partially deployed arrays.

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