PROCEEDINGS OF SCIENCE

V-shaped Cherenkov images of magnetically-separated gamma rays

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A γ ray entering the atmosphere starts an extensive air shower based on e^+e^- pair production in the vicinity of an atmospheric nucleus and subsequent Bremsstrahlung radiation of e^+e^- pairs. We study the showers in which the deflection of the first e^+ and e^- in the geomagnetic field causes the shower to split in two angularly separated components. Based on the Monte Carlo simulations of a subarray of Large Size Telescopes of Cherenkov Telescope Array we evaluate the expected rates of such events. We investigate the potential of a novel geometrical energy reconstruction of such events on the absolute energy calibration of Cherenkov telescopes.

36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

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PoS(ICRC2019)795

1. Introduction

The IACT (Imaging Air Cherenkov Telescopes) technique is based on the measurement of Cherenkov photons produced in the atmosphere by charged relativistic particles forming an Extensive Air Shower (EAS) initiated by a primary γ (or cosmic) ray. The shower image is formed as a two-dimensional angular distribution of Cherenkov light on the camera of the telescope. Classically those images are parametrized as ellipses [1]. The parameters of the ellipses are used to determine the probable type of the primary particle, and to estimate its energy and direction. In the last years the rapid progress of both the hardware developments and new analysis methods resulted in great improvement in the sensitivity of Cherenkov telescopes (see e.g. Fig. 17 of [2]). Using the currently operational IACTs it is possible to obtain for bright flares precision measurements of nightly fluxes with statistical uncertainty of only a few per cent (see e.g. [3, 4, 5]). It should be noted however that the Cherenkov telescopes are burdened by rather large systematic uncertainties, in particular the uncertainty in the energy scale. This uncertainty is the result of the uncertainty in the atmospheric production and absorption of the Cherenkov photons which cannot be easily calibrated due to lack of a “test beam” for IACT instruments. Various relative and absolute calibration methods are applied in IACT analysis, in particular inter-telescope calibration: [6], muon analysis: [7], flux comparisons at different thresholds: [2], LIDAR corrections: [8]). Nevertheless the uncertainty in the energy scale of IACTs is still at the level of $\sim 15\%$ (see e.g. [9, 10, 2]). Such an uncertainty for a typical γ-ray source can easily produce a $\sim 30\%$ systematic error in the absolute normalization of the flux for a Crab-like spectrum, and an even stronger effect for steep spectrum sources and the energies close to the threshold (see e.g. [11]).

The new generation of Cherenkov telescopes will be started with the Cherenkov Telescope Array (CTA) Observatory [12, 13]. CTA is designed to study γ-ray sources from a few tens of GeV to hundreds of TeV with unprecedented sensitivity. It will be composed of sub-arrays of telescopes of different sizes: SST, MST and LST (small, medium and large sized telescope, respectively). In order to fully exploit the scientific potential of CTA, the increase in the statistical accuracy has to be matched also by efforts to lower systematic uncertainty of the measurements. Various studies (both inherited from the current generation of IACTs and new ideas) are being performed to lower the systematic uncertainty of the CTA: using atmospheric monitoring [14], muon calibration [15], cosmic ray electron spectrum [16], inter-telescope calibration [17].

In the case of arrays of surface detectors Geomagnetic Field (GF), i.e. the magnetic field of the Earth is exploited to perform an energy scale calibration due to the observations of Moon or Sun shadow of cosmic rays [18, 19]. In the case of IACTs however, GF has been mostly considered as a nuisance, due to its smearing effect on the images of the showers (see e.g. [20, 21]).

In this work we investigate a special case when the GF effect is strong enough to separate the cascade in two distinct components, causing the occurrence of hereafter V-shaped images. We study if such images can be detected and range of energies when this can happen and develop a toy model that can explain the geometry of such events. We also investigate a simple method for preseletion of such events and use it to estimate expected rates of events with V-shaped images in LST telescopes. Finally, we develop a novel method for verifying the energy calibration of CTA based on a geometrical fit to the V-shaped images.

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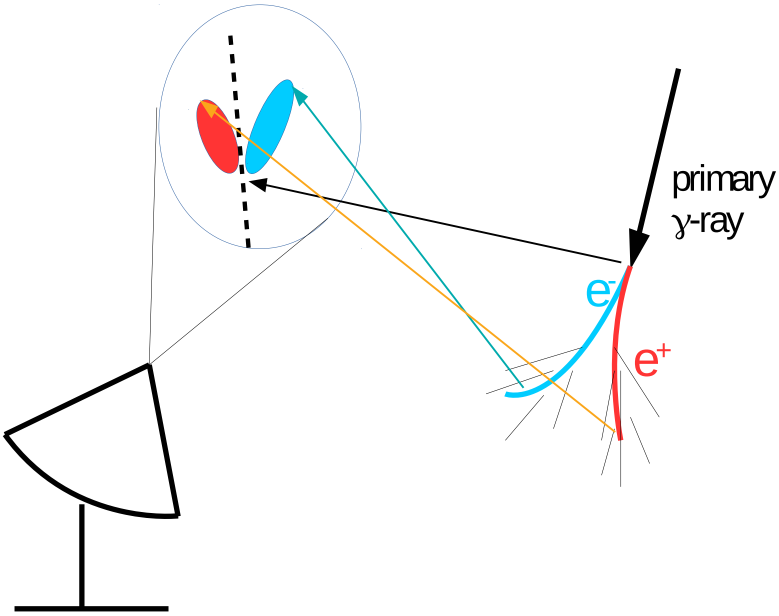

Figure 1: Principle of the generation of V-shaped images. A primary γ ray (black arrow in the right part of the figure) is converted into e^+e^- pair high in the atmosphere. These e^+ and e^- (red and blue lines) are deflected in GF producing further γ rays in Bremsstrahlung process. On the camera of an IACT (left part of the figure) the direction from the telescope position to the first interaction point (start of the both sub-showers) is shown with thin black arrow, while the tail of the both subshowers in shown with teal and orange arrows. The vectors of the primary γ ray direction and of the GF form a plane that is represented in the camera as a thick dashed line. The two subshowers are the red and blue ellipses on both sides of this plane.

2. Magnetically separated events

In order to evaluate the properties of magnetically separated events let us consider a $E_0 \sim 100\,\mathrm{GeV}$ γ ray entering the atmosphere at a low zenith angle. On average after $\sim 9/7$ radiation lengths, i.e. at the height of $H_0 \sim 22$ km it will be converted into a e^-e^+ pair with energies of $E_- = f_{e^-}E_0$ and $E_+ = (1 - f_{e^-})E_0$. Initially, both leptons will be travelling in the nearly same direction as the primary γ ray, however as they move through the atmosphere they will be continuously deflected by the GF in opposite direction. e^+e^- will lose most of their energy over the distance, d_1, corresponding to one radiation length. The characteristic deflection over this distance (assuming $f_{e^-} \approx 0.5$) will be:

$$\Psi_{+-} \approx 2d_1/R_L = 0.1^\circ (d_1/4\,\mathrm{km})(E_0/100\,\mathrm{GeV})^{-1}(B_\perp/0.4\,\mathrm{G}), \quad (2.1)$$

where R_L is the Larmor radius of e^+/e^-, and $B_\perp$ is the component of GF perpendicular to the shower axis. The separation of the order of 0.1° is within the reach of the angular resolution of the CTA telescopes, making it possible to disentangle the two components (started by e^+ and e^-) in the complete image. Such events observed under favourable conditions would produce characteristic V-shaped images (see Fig. 1). An example of a V-shaped image obtained using a full Monte Carlo (MC) simulations is shown in Fig. 2.

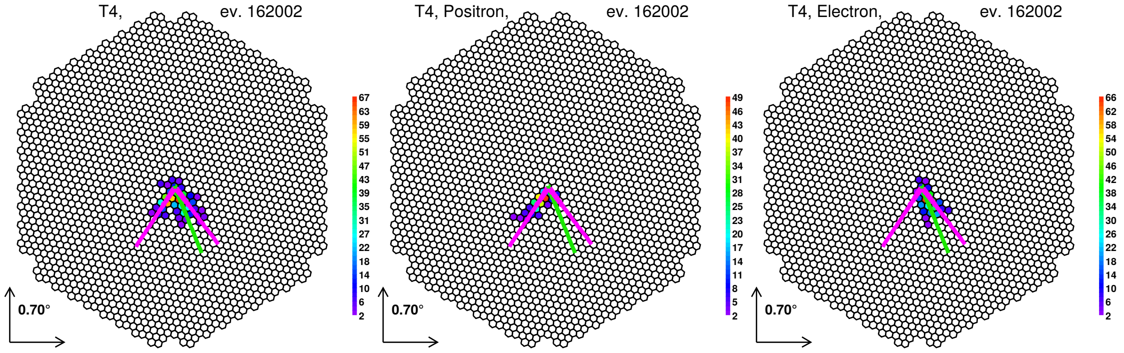

Figure 2: Example of a V-shaped image as seen by an LST telescope. The γ ray with energy 186 GeV has its first interaction at the height of 29.9 km. The left panel shows the whole event, while the middle and right panels show respectively the image produced by subcascade initiated by e^+ and e^- produced in the first interaction. The color scale represents the number of photoelectrons (phe) reconstructed in each pixel. The lines show the predicted by the toy model direction of images: the direction of γ-ray shower if whole image is considered (green) and the direction of e^+ and e^- subcascades (magenta).

3. Simulations and data analysis

We have simulate γ rays with zenith angle of 20° and azimuth corresponding to shower coming from geomagnetic North. The simulations of the shower development were performed using `CORSIKA` version 7.5 [22]. The γ rays are imagined with an array of 4 LST telescopes located in the La Palma site. The response of the telescopes was simulated using `sim_telarray` [23] using settings of the so-called *CTA Prod 3 MC* [24]. Both programs were modified to track the type of the particles produced in the first interaction to the further generations of the cascade starting from those particles, and to the Cherenkov photons produced by the latter. Therefore, for each emitted Cherenkov photon in a γ-ray-initiated shower we know if it originated in the subcascade caused by e^+ or e^- from the first interaction. The extraction of signal amplitudes from simulated waveforms, image cleaning and its parametrization, γ/hadron separation and classical stereo reconstruction and energy estimation is done using `MARS/Chimp` chain [25, 2, 26]. The generated MC simulations are described in more detail in [27].

In order to evaluate the effect of the separation of the primary e^+e^- pair in GF in addition we process the data in 3 ways: (I) considering all Cherenkov photons, (II) considering only the photons from the first e^+ subcascade and (III) considering only the photons from the first e^- subcascade. In order to preselect V-shaped events in (I) analysis we apply, telescope-wise, a fast analytic "double Hillas" procedure. First we calculate the center of gravity (COG) of the full image. Next, the image is split by a line crossing the source position on the camera and the COG of the image. The pixels forming the image are divided into two groups separated by the above-mentioned line and the Hillas parameters are calculated independently for both groups of pixels. We calculate the distance between the COGs of both parts of the image, $\Delta\mathrm{COG_X}$, and the angle (measured on the camera) between the main axes of the two ellipses $\Delta\delta$. The angular distance $\Delta\mathrm{COG_X}$ is defined such that it has a possitive value if the direction of the separation is consistent with the deflection in the simulated GF. In the case of V-shaped images both parameters will have large values.

In Fig. 3 we compare the $\Delta\delta$ vs $\Delta\mathrm{COG_X}$ plot obtained from a combination of the special (II

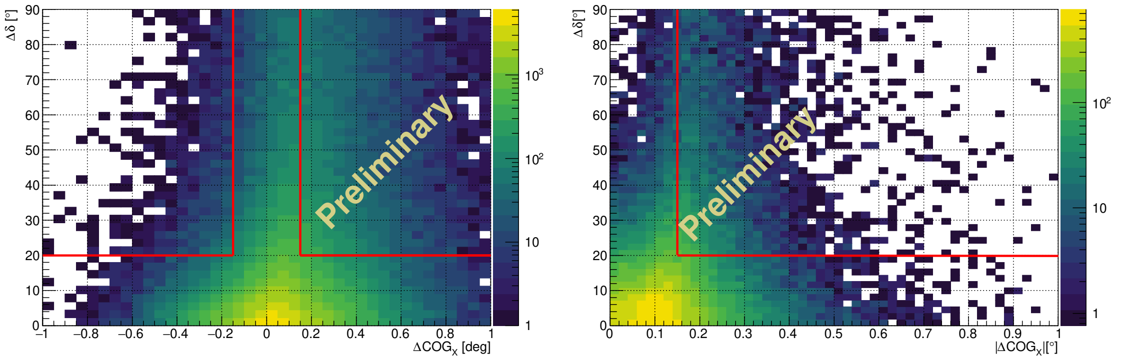

Figure 3: Left panel: angle between the main axis of the e^- and e^+ subcascade images measured on the camera as a function of the distance between the COG of those images. Only images in which the e^+ subcascade and e^- subcascade produce a signal above 50 phe each, and both point in the direction of the source (i.e. the main axis of the ellipse passes close to the source position) are plotted. Thick red lines show the values of the V-image selection cuts $|\Delta\mathrm{COG_X}| > 0.15^\circ$, $\Delta\delta > 20^\circ$. Right panel: same as above, however for the two parts of image from double-Hillas analysis.

and III) analysis with the one obtained from regular MCs (I) in which double-Hillas analysis was used. In the latter case the subimages from e^+ and e^- subcascades cannot be distinguished, i.e. only absolute estimation of $\Delta\mathrm{COG_X}$ can be derived. Due to the deflection in GF, $\Delta\mathrm{COG_X}$ is shifted towards positive values. The classical elliptical events are located at small values of $\Delta\mathrm{COG_X}$ and $\Delta\delta$, while the more interesting, V-shaped events will produce larger values of $\Delta\mathrm{COG_X}$ and $\Delta\delta$. The events with large $\Delta\delta$ but large negative $\Delta\mathrm{COG_X}$ are events in which large fluctuations of the shower mimick the separation due to GF deflection. The distribution obtained with double-Hillas analysis of full images shows a similar shape as the folded along the $\Delta\mathrm{COG_X} = 0$ axis distribution obtained while exploiting the information from which subcascade the Cherenkov photon originates.

Each image selected as V-shaped is fit with a geometrical toy model with 5 free parameters: the core position on the ground, the height of the first interaction, energy of the γ ray E_0, and the fraction f_{e^-} of the energy taken by the first generation e^-. For a given set of parameters the toy model predicts the lines in the camera planes corresponding to the direction of e^+ an e^- subshowers. The details of the model are presented in [28].

In left panel of Fig. 4 we show the rates of events in which at least one/two images are classified as V-shaped. At 100 GeV about 10% (1%) of the events show at least one (two) images with separation of the two components in the double Hillas analysis larger then the applied cuts. For observations of a source with a Crab like spectrum the total rate of the V-shaped events surviving the selection criteria in at least two images is 50 per hour.

4. Absolute calibration of IACTs with V-shaped events

For images selected as V-shaped a geometrical fit of the toy model can be used to obtain an estimation of the primary energy that is in the first approximation independent on the total number of phe registered by the telescope (*size* parameter). Since the *size* parameter is the basic parameter used in the classical reconstruction of the energy in γ-ray showers, comparison of the classical

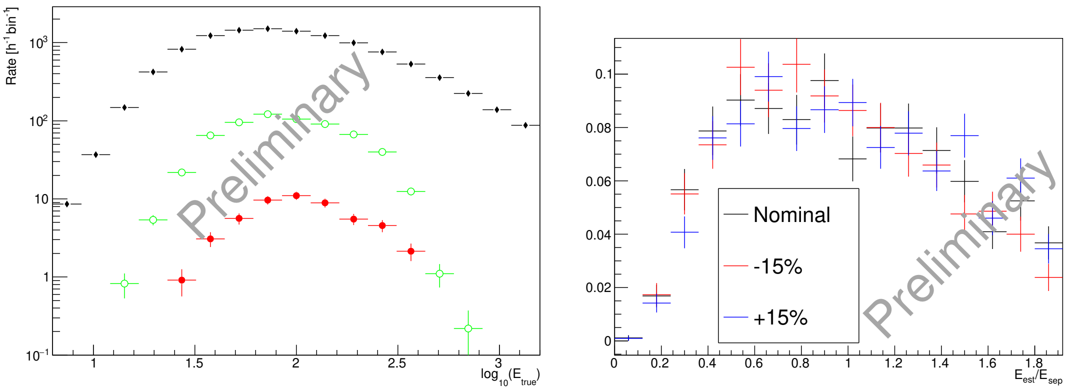

Figure 4: Left: Rate of events surviving V-shape selection cuts in at least one (green open circles) or at least two (red filled circles) images from a source with a Crab-like spectrum. The total rate of reconstructed γ rays is shown as black diamonds. Right: Distribution of the ratio of the energy obtained from the classical stereoscopic reconstruction (including *size* parameter) to the energy obtained in the toy model fitting procedure of V-shaped events. Black lines shows the results for the nominal light yield of the telescopes, while the total light throughput decreased or increased by 15% is shown in red and blue respectively. In the fitting procedure the true values of the source position, core location and height of the first interaction were used. In both panels only events with estimated energy between 30 and 300 GeV are used.

(E_{est}) and geometrical (E_{sep}) reconstruction of the energy can be used to validate and calibrate the light scale of the telescopes.

As a proof of principle of this method we perform the study on three sets of MCs. The first, reference Set A has nominal total light throughput reflectivity values. In the Set B and C we have artificially modified the light throughput by $\pm15\%$ to simulate a systematic uncertainty in the light scale of the telescopes. All three sets are reconstructed using the nominal (Set A) MCs, which causes a systematic bias in the energy estimation of Set B and Set C events. In right panel of Fig. 4 we compare the distribution of E_{est}/E_{sep} for the three sets of MCs. While the shift of the energy scale is partially reflected in the distribution, the effect is very small (the shift of the light scale by $\pm15\%$ results in a shift of the ratio by only $\pm3\%$).

5. Discussion and conclusions

We investigated the occurrence of V-shaped imaged caused by the separation of the e^+e^- pair produced in the first interaction of a primary γ ray by the GF. We derived a simple method to identify the V-shaped images candidates. We derived a toy model fitting procedure that can be used to perform an alternative estimate of the energy of V-shaped events, not dependent on the total light yield of the telescopes. We investigated if the comparison of such an estimate of the energy with the classical one obtained from stereoscopic reconstruction of the shower can be used to validate the energy scale of the Cherenkov telescope. While the change of the telescope reflectivity leaves an imprint on the distribution of the ratio of both energy estimations, in the presented analysis the effect has too small magnitude for the practical application of the method. The fact that the shift of the E_{est}/E_{sep} proxy is smaller then the shift of E_{est} alone is most probably caused by the bias caused by the height of the first interaction. The performance of the method might be improved by using a more refined image fitting algorithm, possibly using templates of the two subshowers (see e.g. [29]).

Acknowledgement

This work is supported by the grant through the Polish Narodowe Centrum Nauki No. 2015/19/D/ST9/00616. DS is supported by the Narodowe Centrum Nauki grant No. UMO-2016/22/M/ST9/00583. This work was conducted in the context of the CTA Analysis and Software Working Group. We gratefully acknowledge financial support from the agencies and organizations listed here: `http://www.cta-observatory.org/consortium_acknowledgments`.

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